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16. Abstract (MAXIMUM 200 WORDS)
The United States Coast Guard (USCG) maintains approximately 15,000 buoys on 7,400 miles of the Western Rivers system. About half of them are replaced each year at the cost of about $3M. This project evaluated existing hardware and operations to determine if alternative buoy designs could increase buoy life and reduce overall costs. A literature search was performed, including studies on fast water and debris-shedding buoys from the 1970's, a 1991 buoy technology survey, and a 2006 USCG Academy (USCGA) research project of fast water buoys, in order to identify potential buoys and their characteristics that could meet basic criteria. No physical tests were performed using buoys as part of this effort. As no existing buoy designs satisfied all the needs for fast-flowing and pooled waters, hybrid buoy designs, incorporating features and materials from existing buoys, were developed through analysis of the salient features of existing buoys. The resulting buoys may be suitable replacements for existing USCG 4th Class and 6th Class buoys used on the Western Rivers system. The hybrid buoy design consists of an ionomer foam body construction with a steel mooring bar and rudder fin. The hybrid buoys are shaped to the same design as existing USCG 4th Class and 6th Class buoys, but their overall size is smaller. Initial start-up cost may be greater than existing USCG 4th and 6th Class buoys. The 4th Class hybrid buoys are anticipated to have longer buoy lives, reducing number of buoys to be purchased. They should use the current chain and sinker mooring system because of its proven functionality. The new design could also reduce the workload of the inland buoy tenders (WLR). It is recommended that detailed design and analysis be completed on the 4th Class hybrid buoy; but no additional efforts should be made for the fast water design at this time because the additional costs do not appear to provide increased buoy longevity and decrease costs. Additional testing needs to be done to confirm the analysis.

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EXECUTIVE SUMMARY

The United States Coast Guard (USCG) maintains approximately 15,000 buoys on 7,400 miles of the Western Rivers system. The conditions that are present in the Western Rivers require approximately 7,500 river buoys to be replaced annually at a cost of about $3M. The primary objective of this effort was to develop alternative buoy designs to increase operating life of the buoys and thus reduce overall costs. In addition to the buoy design, the associated equipment that is used to moor and anchor the buoys was investigated. Visits were made to three inland buoy tenders, rivers (WLRs) to familiarize all personnel involved in the project with actual buoy tender operations. Buoys were seen that had been damaged by being overrun by tows as well as those requiring replacement because of normal environmental wear and tear.

A literature search was performed, including studies on fast water and debris-shedding buoys from the 1970's, a buoy technology survey from 1991, and a 2006 United States Coast Guard Academy (USCGA) research project of fast water buoys. From these studies, existing or previously designed candidate buoys were selected, as well as desired characteristics that included those that help to define or affect longevity such as weight, height, diameter, ability to handle currents, visibility and radar reflection. Once all the candidate buoys were identified, comparisons of their characteristics were accomplished to determine which of the candidate buoys could offer improved performance over the existing 4th Class and 6th Class buoys. This process was designed to eliminate buoys from consideration that did not meet the criteria as well as identifying characteristics that could provide longer buoy life. Tests of the actual buoys were not performed, only analysis of existing specifications. No existing buoy characteristics satisfied all the needs for fast-flowing and pooled waters. Therefore, hybrid buoy designs were developed, through analysis of the salient features of the existing buoys and incorporating properties and materials from existing buoys.

The resulting hybrid buoy design consists of an ionomer foam body construction with a steel mooring bar and rudder fin. The foam body is more resistant to damage from collision than the existing steel buoys, which permanently deform. The sub-surface steel construction will provide the structural integrity needed to handle varying currents by providing multiple mooring configurations and a rudder fin to add stability. The hybrid buoy design utilizes an internal radar reflector, making it less susceptible to damage when overrun. The hybrid buoys are shaped to the same design as the existing USCG 4th Class and 6th Class buoys, but their overall size is smaller. Compared to the USCG 4th Class, the hybrid design has the same diameter and footprint; however, the hybrid buoy is 32 percent shorter, 50 percent lighter, should handle 70 percent greater currents, have increased visibility; but is estimated to be twice as expensive. Compared to the USCG 6th Class, the hybrid design also has the same diameter and footprint; however, the hybrid buoy is 38 percent shorter, 50 percent lighter, may handle 15 percent greater currents, and maintains visibility, and may be about 20 percent more expensive.

After extensive analysis, the recommended buoy for pooled water should be the 4th Class hybrid design due to its overall performance as well as its ability to remain servicable for longer periods of time, thus reducing maintenance costs. The initial start-up cost is greater than the existing USCG 4th Class buoys, but the hybrid buoys are anticipated to have longer buoy lives, reducing the number of buoys to be purchased. It should utilize the current chain and sinker mooring system because of its proven functionality. It is recommended that the "pooled" hybrid design be investigated further in field trials. The fast water design should not be pursued further because gains in buoy longevity are unlikely to be realized.

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LIST OF ACRONYMS

AMSEC	AMSEC LLC, a Division of Northrop Grumman
AOR	Area of Responsibility
ATON	Aids to Navigation
CG	Center of Gravity
CG	Coast Guard
DPW	District Waterways Management Branch
HWV	Heartland Waterways Vessel
IALA	Association of Lighthouse Authorities
ORD	Operational Requirements Document
PIANC	International Navigation Association
R&DC	Research & Development Center
USCG	United States Coast Guard
USCGA	United States Coast Guard Academy
USCGC	United States Coast Guard Cutter
UV	Ultraviolet
WLR	Buoy Tender, Rivers

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1 INTRODUCTION

1.1 Background

The United States Coast Guard (USCG) is planning to replace its buoy tender, rivers (WLR) fleet, which accomplishes aids to navigations (ATON) and other missions on the Western Rivers. Plans call for the replacement of these vessels in a 5- to 10-year time-frame with a heartland waterways vessel (HWV). During the process of developing the Operational Requirements Document (ORD) for this new vessel, the Coast Guard (CG) ATON Program Manager (Commandant (CG-54131)) has determined that the ORD Development Team requires a better understanding of the future ATON workload of these vessels. As a result, Commandant (CG-432) has been requested to conduct an analysis that forecasts the anticipated HWV workload associated with the type of buoys that will be used on the Western Rivers in the next 5 to 30 years by evaluating new potential buoy designs that could reduce this workload. But any new buoys must still be compatible with hardware on the existing WLRs.

The Western Rivers for the purpose of this report are defined as the Mississippi River from Upper Mississippi River Mile 857 to Lower Mississippi River Mile 155. It also includes whole or part of the following rivers and waterways: Alabama, Arkansas, Black Warrior, Green, Missouri, Monongahela, Ohio, and Tennessee Rivers, as well as the Tennessee-Tombigbee and various other waterways, as seen in Figure 1.

Figure 1. Western River System of the United States (Reference 1).

The USCG maintains approximately 15,000 buoys on 7,400 miles of river. These waterways can be categorized as either "pooled" or "fast/open" water. The pooled waters are where the rivers are divided into series of pools by locks and dams created by the Army Corps of Engineers to control the river's varying water levels (Reference 6). The water can be restricted and currents reduced to as low as 1 knot, and the water levels raised or lowered to be consistent. For example, during the wetter months of the year, the water levels will rise and potentially flow over the river banks. To prevent this, the dams and locks are opened to lower the water level, but allow more water into the system causing higher currents up to 7 knots for brief periods. Debris accumulation on buoys is not a factor to consider in pooled water because the average low currents do not tend to carry debris as significantly. The lower currents also do not cause the frontal surface of the buoy to retain debris, thereby preventing the increase in the overall buoy drag, unlike what happens in fast-flowing waters. Weather conditions such as rain and spring thaws can also cause the water levels to rise within the river system.

The fast-water current is unrestricted and can range from 3 to 8 knots with an average of 5 knots, carrying significant amounts of debris (Reference 6). These unrestricted waters will typically flow at higher currents than the pooled water, but will also flow faster when influenced by weather conditions such as rain and spring thaws. The fast-flowing waters will carry debris at a higher rate, providing the opportunity for debris to accumulate on the buoy frontal surface, increasing the buoys overall drag and causing submergence at lower currents.

The conditions that are present in the Western Rivers require approximately 7,500 river buoys to be replaced annually at a cost of about $3M. Many of these are run over by tows but others are damaged by debris or their color fades reducing their visibility. While the cost for the individual buoys is not large, the accumulation of numbers and the hours required for replacement is substantial. Inland tenders must revisit most of the buoys every two weeks, putting a strain on operations. During the underway period, or time in which a buoy tender performs operations, the area of responsibility (AOR) of that tender is visited; however, its frequency and percent covered differs depending on pooled waters versus fast-flowing waters. In fast-flowing waters, the buoy tenders are underway for one week and in port for another week. The buoy tender will cover all of its AOR in one underway period and return to port to perform any necessary replenishment and operations. In pooled waters, the underway period is one week, in which only a portion of its AOR is visited, and one week in port. Pooled water tenders can also modify their schedule to be underway two weeks and then in port for two weeks depending on varying situations (Reference 1).

In order to identify the issues that influence the workload of the WLRs, the factors that influence buoy life must be determined to see how changes can affect the time needed for the inspection and maintenance of the buoys. The buoy system encounters many service factors, both environmental and man-made, that result in their decreased service life and requirements for additional maintenance. These factors include:

- Environmental Factors
  - Color fading
  - Material corrosion
  - Loss due to diving
  - Bird droppings
  - Debris accumulation
- Man-Made Factors
  - Damage from collision
  - Mooring configurations for current

Loss due to diving occurs when the buoy is dragged beneath the surface from higher currents, increasing the forces on the mooring equipment until the force exceeds the buoyancy of the buoy. This will cause the buoy to submerge and can cause the mooring line to break and allow the buoy to drift off station. The mooring configuration is also an important factor because the existing USCG 4th Class and 6th Class buoys provide varying mooring points to compensate for differing water currents. If the buoy is improperly moored, it can lean at lower currents and submerge earlier than expected.

In addition to the buoy design, the associated equipment that is used to moor and anchor the buoys was investigated based on technical specifications and use guidelines. The existing mooring system consists of wire or chain that is susceptible to corrosion and chafing damage from currents. Wire rope was said to be used in fast-water operations due to its higher breaking strength and ease of handling. Steel chain is being used in areas of lower currents because there is no need for greater strength and it handles chafing better, as being in contact with itself or the bottom causes wear. It was observed that the USCGC OUACHITA utilizes half-shots (45 feet) of chain rather than a full shot (90 feet) because of varying depths in its AOR. The buoy anchor, or "sinker," is a block of cement with steel eye loops for lifting and attaching the mooring line. The study also addresses possible alternatives for the mooring lines and sinkers, including the use of synthetic lines.

The majority of the floating aids in the Western Rivers system are 4th Class and 6th Class buoys and the study has concentrated on suitable replacements for these two types, with characteristics shown in Table 1 (References 2 and 17). These buoys are constructed of mild steel and filled with foam. The design goals for these systems include:

- No reduction in service over current systems provided to the mariner.
- Reduced maintenance tasks required from the HWV.
- Lower total ownership cost compared to the present system.

Table 1. Existing USCG river buoys.

Type	Name	Weight (lbs.)	Diameter (ft.)	Length (ft.)
USCG 6th Class Can	6 CR	160	1.50	7.25
USCG 6th Class Nun	6 NR	165	1.50	8.67
USCG 4th Class Can	4 CR	465	2.25	9.25
USCG 4th Class Nun	4 NR	470	2.25	10.44

1.2 Methodology

The study began with visits to three inland WLRs to learn more about the equipment, buoys and operating procedures on board each vessel. Observations were made for operations in both "pooled" and fast flowing waters.

Next, a literature search of previous studies in buoy technology was accomplished to determine the state-of-the-art world-wide and to select potential candidate buoys for use in fast flowing and pooled waters on the Western Rivers system. Pertinent references were also provided by the USCG Research & Development Center (R&DC) at the project kick-off meeting and included previous R&DC studies as well as other buoy data. Other sources were to be searched, including:

- International Association of Lighthouse Authorities (IALA)
- International Navigation Association (PIANC)
- Society of Naval Architects and Marine Engineers

The material was reviewed and pertinent references were identified and synopsized as appropriate. No physical tests were done; but the analysis included reviews of other tests and analytical calculations to determine buoy performance. Based upon the results of the literature search and visits to WLRs, criteria were selected for the potential buoy systems. These included:

- Improved performance in currents for buoys in fast flowing waters
- Ease of deployment and retrieval, with no major changes to existing WLR handling and storage requirements
- Improved ability to handle collisions and debris build-up
- No reduction in service to the waterway user; i.e., equal or greater visibility and radar range
- Increased service life with reduced maintenance requirements for the WLR and the future HWV. This requirement is somewhat subjective and based on how well the other performance parameters hold up over time.
- Lower costs compared to the present system

The study also included the evaluation of the moorings and sinkers, with the goal to produce a balanced system, with all components having the same service life.

Once the candidate systems were identified, their characteristics (provided by reports and from manufacturers) were compared to performance criteria, including visibility, radar range, performance in currents, durability, and handling. The performance evaluation criteria were based on discussions with the USCG sponsor and weighted to put the emphasis on service to the waterway user. This criteria was based on specific buoy characteristics that all contribute to the operating life of the buoy. Cost of the alternatives was a secondary consideration and evaluated later. The most promising candidates were selected for further analytical evaluation and presented to USCG R&DC and ATON personnel.

Since all of the buoys possessed some undesirable characteristics, it was recommended to combine the best attributes of all of them into a new design that would be compatible with existing hardware on the WLR. Based on the attributes of the most promising candidates, preliminary designs of hybrid buoys using new materials were developed following the shape of the existing buoys. The structure, hydrodynamics, moorings, and anchors were analyzed and evaluated using the same criteria used to select potential candidates and eliminate others. The resulting buoys are potential replacements for the existing buoys in fast flowing and pooled waters. Details of the process, the candidate buoys, the selection criteria, the analyses, and the resulting designs are presented in the remainder of this report.

2 WLR VISITS

2.1 Introduction

Visits were made to three inland WLRs to familiarize all personnel involved in the project with actual buoy tender operations. There were the CGC Kankakee in Memphis, the CGC Ouachita near Chattanooga and CGC Osage downriver from Pittsburg. Buoy launch and recovery operations were observed and discussions were held with WLR personnel to gain insights into their daily operations and their experience with other inland and coastwise cutters. The Kankakee was operating in “fast-flowing waters,” which occur on most

major rivers and other two were operating in "pooled waters," which occur between dams on many of the inland waterways. The operations of each of the three WLRs are described as a trip report in Appendix B.

2.2 Summary of Conditions

The Western Rivers system requires buoys that can withstand varying environmental and man-made conditions. Some of these conditions were listed in Section 1.1 and will be summarized and elaborated on within this section. These conditions affect daytime visibility, radar reflectivity, and service life. Daytime visibility is hindered by the fading color of the daymark, bird droppings covering the paint, natural debris increasing buoy drag, and excessive currents causing the buoys to submerge or dive. Submergence and inclination of the buoy in currents also reduce radar reflectivity. Based on water conditions, the currents for the pooled waters range from 1 to 7 knots with an average of 1-2 knots and varying water levels, while the fast-water current range from 3 to 8 knots with an average of 5 knots, as shown in Reference 6, carrying significant amounts of debris. These conditions require frequent maintenance, observation, and replacement of the river buoys. The service life of the buoy is reduced by corrosion of the steel shell leading to filling with water, causing the buoy to have reduced freeboard or be lost due to diving (Figure 2). Corrosion and chafing can also cause the mooring links to part, resulting in the buoys moving off station. The environment is not the only contributing factor to the reduction in service; man-made conditions of debris and damage from collision also contribute to the buoys being lost due to diving (Figure 3). The varying currents also contribute to the buoy visibility by causing the buoy to incline depending on the mooring point used when the buoy was set. As seen in Figure 4, the buoys can either incline towards or away from the river current and hinder the buoys performance. One buoy was off station because of a chafed chain which had parted and allowed the buoy to drift. See Figure 5.

Figure 2. Corroded buoys requiring maintenance.

Figure 3. Buoys damaged from collision.

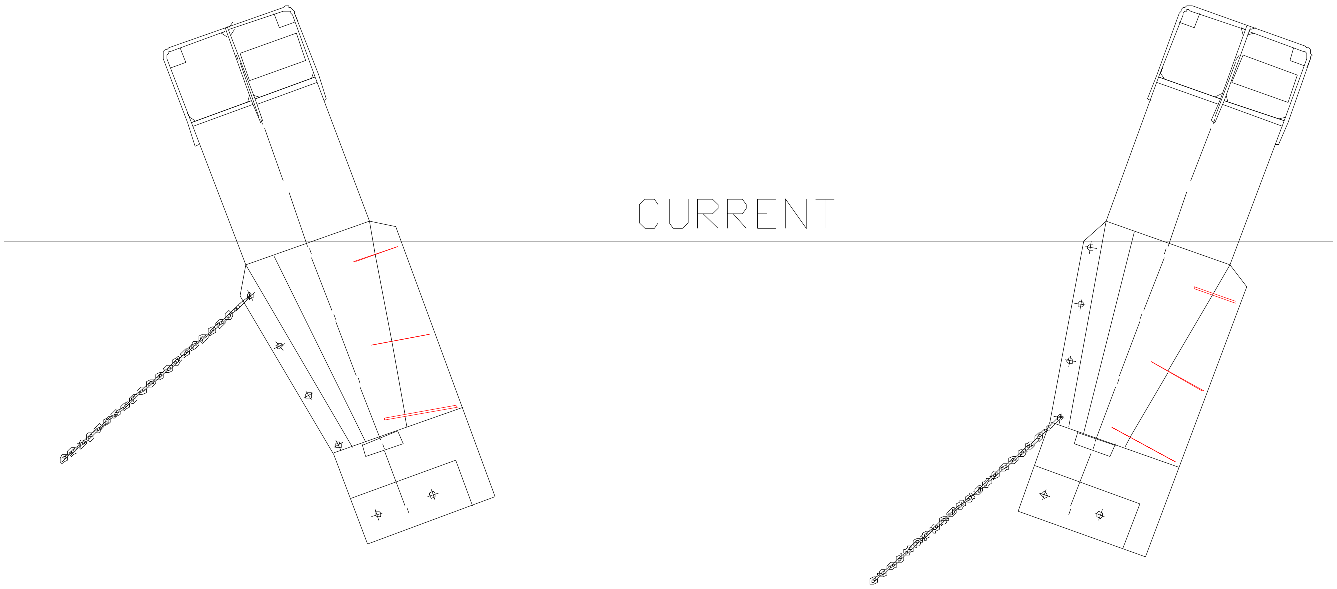


Figure 4. Mooring point and buoy inclination.

Candidate buoys were evaluated using criteria based on these conditions, allowing the selection of candidates that could outperform the existing USCG system.

Several operational procedures were noted:

- Each of the Master Chiefs in charge of the WLRs visited was keeping his own spreadsheet record of the buoys he had deployed. If the buoy was deployed before his command, he had no data as to when the buoy had been set, whether it was new or reconditioned, the age of the mooring, etc. A uniform system for tracking buoys on the Western Rivers should be developed and maintained by the Master Chiefs. This system would provide a database for the determination of actual buoy service life and provide reference data for the evaluation of future buoys.
- In fast water operations, the buoy, mooring, and sinker are all pulled up when a buoy was reset. This provides an opportunity to inspect the entire system and replace components as needed. In pooled waters, only the buoy was retrieved, with a minimum of chain pulled up. A sufficient length of chain should be pulled up each time a buoy is retrieved to inspect a representative length to assure the crew of the chain's suitability for continued service, as is done for coastal buoys. Such inspection would prevent the condition seen in Figure 5.
- Inspection of the wire rope and chain appeared to be strictly visual, with no set criteria for allowable loss. Measurements should be made in accordance with the ATON Manual (Reference 17), or a similar procedure established.
- The recovery of buoys was done either by lassoing or the use of a boat hook and seemed to vary from WLR to WLR based on tradition on that cutter. The boat hook appeared to be the more positive technique, but the relative merits of each should be studied and a uniform procedure adopted.

These observations are not meant in any way to be critical of the WLR operations, but might provide opportunities for improvement and standardization. The cooperation of the three WLR crews during our visits is sincerely appreciated by all and contributed greatly to the understanding of WLR operations.

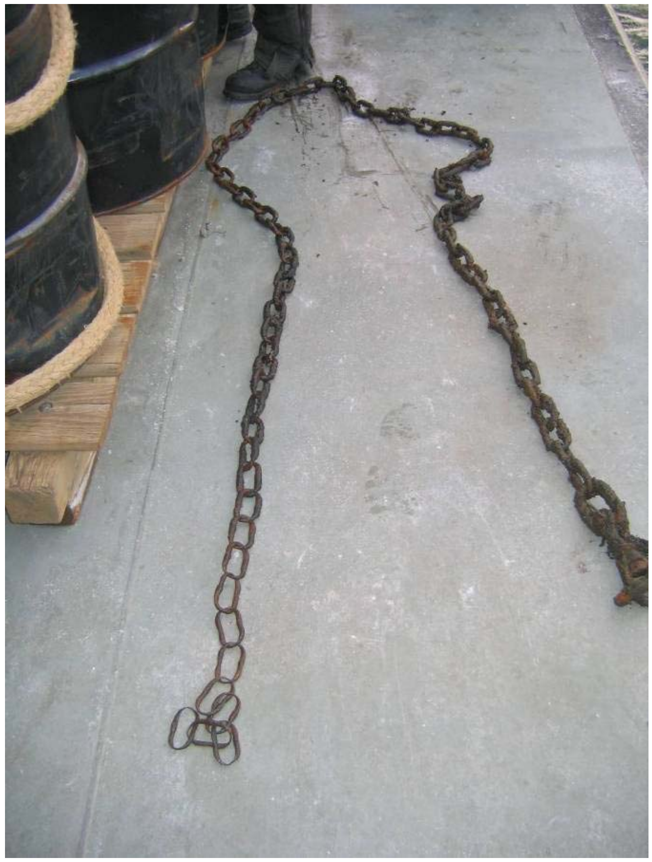


Figure 5. Chafed chain from off-station buoy.

3 SCOPE OF WORK

3.1 Buoy Evaluations

To identify the type of buoys that could be used on the Western Rivers, an evaluation using the existing data and manufacturer's information was performed of the technologies projected to be used in the future for inland river buoy systems, including the buoy, mooring (chain and anchor), and other attachments required for buoy deployment. This was done by evaluating existing buoy characteristics and buoy designs and identifying what aspects made these desirable or undesirable. Following identification of technologies, candidate systems were synthesized and evaluated analytically. These criteria scores were then combined with longevity and cost issues for the final recommendations.

The primary objective was to investigate alternative buoy designs to replace the existing technology, optimize overall operation and increase buoy life. To characterize these improvements, any new buoys would need to maintain or exceed the current levels of service, reduce overall maintenance need, increase longevity and potentially reduce the cost of ownership. To achieve this objective, several resources were investigated to determine existing buoy technology as well as to research, evaluate, and quantify additional available resources. Based on the data available, several characteristics could be identified as the primary causes for debris accumulation and damage and loss from collision.

3.1.1 Existing Conditions and Technology

In the visits made to the three WLRs based on the Western Rivers, different types of water flow operations were observed and separated into fast-flowing and pooled waters.

The Memphis-based USCGC KANKAKEE experienced fast-water operations utilizing 4th Class buoy practice and provided feedback to the affect of the mooring point to the riding attitude of the buoy. Buoys were also seen that were damaged from being overrun by tows. Some of these buoys were able to be repaired, repainted, and reused, but many were waiting to be scrapped because of excessive damage or loss due to sinking. The crew also provided guidance for issues pertaining to color fading, debris accumulation, recovery, and stowage.

The Chattanooga-based USCGC OUACHITA and Sewickley-based USCGC OSAGE operate in pooled waters utilizing both 4th Class and 6th Class buoys. The crews stated that the buoys require frequent maintenance because of damage and color fading, which includes bird droppings. Feedback was provided regarding chain chafing and corrosion, causing the buoys to move off station as well as requiring additional maintenance. The crews state that debris was not a major factor in the pooled water operations, unlike in fast-flowing waters.

As the first step of the evaluation, the candidate buoys were separated into the type of water flow for which they were designed for and best suited. Fast-flowing water buoys were classified as being able to handle currents greater than 4 knots. From there, separate guidelines were established to evaluate those considered in each category, as seen below.

- Fast-flowing Water
  - Ability to handle currents: 3 - 8 knots/5 knot average (Reference 6)
  - Ease of deployment/retrieval: compatibility with existing WLRs
  - Debris/survivability: collision damage/resistance to elements
  - Radar/visibility range maintain current capability as a minimum
- Pooled Water
  - Ability to handle currents: 1 - 7 knots/1-2 knot average (Reference 6)
  - Ease of deployment/retrieval: compatibility with existing WLRs
  - Durability/longevity: resistant to elements
  - Radar/visibility range maintain current capability as a minimum

3.2 Mooring Lines

As stated in Section 3.1.1, the moorings which secure the buoys to their anchors experience environmental loadings including chafing and wastage. It is desirable that the service life of the mooring system match that of the buoy to more efficiently perform operations and not require additional trips for each different component of the system. Conditions can be seen as common between pooled and fast-flowing waters, both requiring a more durable system. For fast-flowing water, the use and handling of wire systems is to be evaluated. For pooled water, the use and handling of chain systems is to be evaluated. The use of synthetic lines is to be investigated for the potential increase in service life and ease of handling. For pooled water operations, which include replacing a buoy during chain replacement because of maintenance, increasing the overall chain life to match the life of the buoy is the intended result.

3.3 Sinkers

To securely anchor the buoys at their stations, cement sinker blocks are used, attached to the mooring lines. During service life of the anchors, the sinker eye loops become worn by chafing, occasionally causing the buoys to drift off their station. For fast-water operations where the sinkers are handled regularly, an additional concern is easier stacking and handling, as well as increased service life.

4 EVALUATION AND CONCLUSIONS

4.1 Literature Search

To locate information about the characteristics of existing and experimental buoys, reports and manufacturers' information was reviewed. Since this project did not conduct any testing, decisions about potential useful buoys was only determined by evaluating the existing data.

4.1.1 Worldwide Buoy Survey, 1992 (Reference 2)

A buoy technology survey was performed in 1991 to evaluate the buoy design technology used around the world. Each buoy surveyed was evaluated based on dimensions, features, material, and additional performance characteristics. For the purpose of this project, only inland river and spar buoys were extracted from the survey and investigated. Buoys that were judged suitable for further investigation were shallow and slow current, fast water, catamaran, and inshore buoys. Buoys that support lights were investigated further to determine if the removal of the light would present a viable option for further comparison. Once all of the candidate buoys were determined, further investigation and comparison were performed to determine which of the candidate buoys had the potential to offer improved performance over the existing 4th Class and 6th Class buoys.

The ability to shed debris and survivability was not a priority used in the initial 1991 evaluation; however, it will be discussed further in Section 4.1.3. Survivability is also associated with the buoys' ability to resist damage from collision, which will be investigated with the concept of new and different materials, which is seen in Section 4.2. The ability to handle currents as reported in the survey was used to divide the buoys into the water flow classification. Storage, handling, compatibility with the existing WLRs, and radar/visibility were evaluated within the table based largely on the buoy size and weight.

Using the criteria from Section 3.1.1, the selected river and spar buoys are listed in Table 2, Table 3, and Table 4. The current handling data for the spar buoys was not provided so they were given a zero (0) although it is expected that they could handle some current or brief surges typical in a "pooled" river. These tables list the buoys and the characteristics that were considered relevant to the evaluation. Drawings of the buoys are provided in APPENDIX A.

Table 2. Selected standard buoys and characteristics: 6th Class buoys.

	Type - Name	Location	Weight (lbs.)	Material	Current (Kts)	Visibility (Nmi)	Radar (Nmi)	Diameter (ft.)	Length (ft.)
6th Class Buoys									
	6 CR	USCG	160	Steel/Foam	2.5	1.0	1.0	1.50	7.25
	6 NR	USCG	165	Steel/Foam	2.5	1.0	1.0	1.50	8.67
	CB-100	Japan	57	Plastic	4.0	0.3	0.4	1.64	5.90
	Inland Unlighted STD	Germany	106	Steel/Polyurethane	3.0	1.7	1.0	3.44	7.09
	FA-2010	Canada	2838	Steel	3.0	2.0	5.7	4.00	15.58
	FA-2011	Canada	3065	Steel	3.0	2.0	5.3	4.00	14.27
	FA-1001	Canada	3876	Steel	3.0	1.9	3.2	4.59	17.25
	FA-2008	Canada	1047	Steel	3.0	1.5	3.9	3.00	9.84
	FA-2009	Canada	1094	Steel	3.0	1.5	3.9	3.00	8.86
	FA-2015	Canada	159	Steel	2.5	1.0	1.5	1.51	6.14
	FA-2016	Canada	165	Steel	2.5	1.0	1.5	1.51	7.86

Table 3. Selected standard buoys and characteristics: 4th Class buoys.

	Type - Name	Location	Weight (lbs.)	Material	Current (Kts)	Visibility (Nmi)	Radar (Nmi)	Diameter (ft.)	Length (ft.)
4th Class Buoys									
	4 CR	USCG	465	Steel/Foam	5.0	1.4	1.5	2.25	9.25
	4 NR	USCG	470	Steel/Foam	5.0	1.4	1.5	2.25	10.44
	CP-2800 - Catamaran	India	508	GRP/Foam	8.0	0.0	0.0	0.82	9.19
	FA-2013	Canada	350	Steel	4.5	1.4	1.5	2.00	8.72
	FA-2012	Canada	300	Steel	4.5	1.5	1.5	2.00	8.79
	FA-2014 - Catamaran	Canada	147	Steel	8.0	0.0	1.5	1.67	7.97

Table 4. Selected spar buoys and characteristics.

	Type - Name	Location	Weight (lbs.)	Material	Current (Kts)	Visibility (Nmi)	Radar (Nmi)	Diameter (ft.)	Length (ft.)
Spar Buoys									
	FA-3007 0.3m, Ottawa	Canada	152	Steel/Foam	0.0	1.1	2.5	1.17	7.66
	FA-3008 Vari. Buoy.	Canada	26	GRP/Foam	0.0	1.1	0.0	0.61	10.00
	FA-3006 0.6m Short	Canada	673	Steel	3.0	1.5	3.3	2.04	12.75
	FA-3005 0.6m	Canada	1125	Steel	5.0	1.5	3.4	2.04	18.05
	50/120 Pastic	Finland	0	Polyethylene	0.0	0.7	0.0	0.36	9.85
	160 mm x 6 m Plastic	Finland	58	Polyethylene	0.0	1.3	0.0	0.53	19.68
	225 mm x 7 m Plastic	Finland	122	Polyethylene	0.0	1.7	0.0	0.74	23.00
	90/160 Plastic	Finland MFG-1	0	Polyethylene	0.0	1.2	0.0	0.53	9.85
	T-86 Spar Buoy	Germany	6170	Steel	0.0	2.5	5.4	4.92	24.50
	Selco Type 5	Norway	110	Fiberglass/Foam	0.0	1.3	0.0	1.38	14.11
	Selco Type 4	Norway MFG-1	99	Poly/Foam	0.0	1.5	0.0	1.35	25.10
	SF-5 Spar Buoy	USA MFG 1	3877	Steel	3.0	1.9	3.2	4.59	17.25

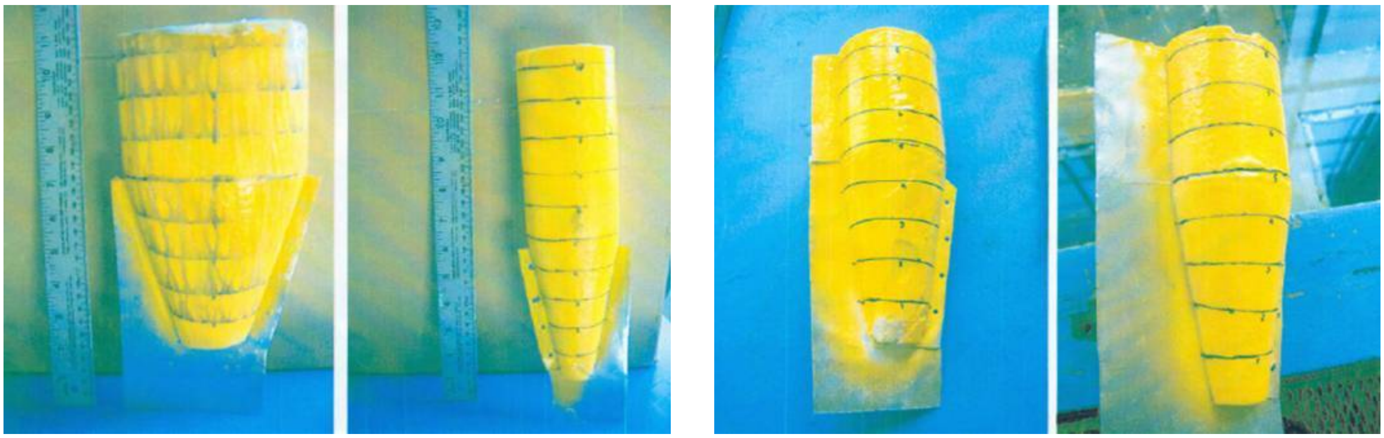
4.1.2 USCG Academy Fast Water Buoy Design, 2006 (Reference 4)

In the United States Coast Guard Academy (USCGA) cadet research project, buoy designs capable of handling fast-flowing water currents were developed and compared to the existing 4th Class river buoys. The report mentions that the existing buoy system cannot maintain proper function with fluctuating water levels and excessive debris accumulation caused by water flowing in excess of 7 knots. The existing buoys cannot maintain visibility and position and may be lost under these conditions. It was determined during the initial phase of the USCGA report that an altered design needs to be developed to counter and overcome the river conditions. The end results of the report focus on the current velocity, setting aside debris accumulation. Debris accumulation is discussed further in Section 4.1.3.

The report mentions previous research performed in the development of hemispherical and discus buoys to counter the fast-water conditions. However, these designs were not considered to be feasible because of cost, weight, handling, and stowage incompatibilities. New designs were developed based on theoretical calculations, which yielded four concept models that were built and tank tested. These concepts were developed utilizing the existing 4th Class buoy as a baseline.

The concepts and their notable characteristics are as follows:

- Small elliptical buoy: Smaller footprint/drag reduction (Figure 6 (b))
- Large elliptical buoy: Larger footprint/drag reduction (Figure 6 (a))
- Large fin buoy: Additional full buoy length larger splitter plate (Figure 6 (d))
- Small fin buoy: Additional full buoy length splitter plate (Figure 6 (c))



(a) Large Elliptical **(b) Small Elliptical** **(c) Small Fin** **(d) Large Fin**

Figure 6. Four concept models developed based on theoretical calculations (Reference 4).

The elliptical buoys retained the same fin configuration as the original 4th Class buoy. After performing tests on the models, it was concluded that the "small elliptical buoy" displayed the greatest improvement in reducing buoy drag and line tension and had a smaller footprint allowing additional buoys to be stowed. The negative aspects of this design are that the buoy needs to have an increased overall length to maintain buoyancy and that the buoy was observed oscillating "back and forth on its mooring," resulting in additional load being applied to its mooring. The other design that performed well was the "small fin buoy" with significant drag reduction for a simple modification, while providing a similar stowage configuration. The negative aspect of this design was that it could be difficult to retrieve by lassoing.

It can be concluded from the USCGA design modifications that an improved fin or rudder plate with provisions for retrieval would be an option to be included in the design of improved fast-water buoys. The elliptical shaped buoy would increase the construction costs and present problems in handling. In general, improvements to the underwater shape and increases in the size of the rudder reduced buoy drag and improved performance.

4.1.3 Debris Shedding Test Report, 1974 (Reference 5)

Based on the Project 2510 – Buoy Hulls, Debris Shedding Test Report from January 1974, existing fast flowing water buoys were not adequate in shedding debris and tended to dive due to debris accumulation. From previous research, the buoy designs seemingly best suited for evaluation were the saucer, discus, and hemispherical hulls that performed best with currents up to 7 knots. However, it was seen that these buoys were more prone to debris accumulation because the mooring point was located near the water surface, causing the hull to ride at an acute angle and allow debris to collect on the mooring line.

Proposed design developments to these hulls were to attach a mooring rod extension to the underside of the hull, lowering the mooring point and preventing the buoy from riding at an acute angle. Initial concerns were found with this modification. The mooring rod had to lower the mooring point greater than 18 in. to prevent debris from slipping beneath the hull and collecting on the mooring rod. It was concluded from this improvement that a mooring rod continues to provide a small diameter object near the surface where debris can accumulate. It was stated that the existing 4th, 5th, and 6th Class buoys could shed the debris better than this modification because of the large surface diameter and position of mooring line well below the surface. Debris is known to deflect to the side rather than below the hull.

The three buoy hull designs tested did not improve debris shedding, but in fact presented additional problems. The saucer buoys had insufficient freeboard, causing the water to flow onto the leading edge of the buoy. This issue led to the buoys “diving” shortly after deployment. The discus buoys were seen riding at about 30 - 40 degree trim aft, preventing debris from shedding and allowing it to collect on the mooring line. The debris accumulation would also cause the buoy to “dive” beneath the water surface. The riding attitude was improved by locating the mooring rod extension forward, preventing subsurface debris accumulation. The hemispherical buoys trapped subsurface debris similarly to the discus buoy, causing the buoy to be dragged off station. The buoy was seen not “diving” as significantly because of its large reserve buoyancy.

The report concluded that the existing 4th Class and 6th Class buoys shed debris better than any of the alternatives considered, but the research established criteria for avoiding debris accumulation which will be incorporated in the concept design. As seen in Figure 7, the standard river buoy provides an obtuse mooring line angle, less likely to trap debris, unlike the hemispherical and other fast water buoys that form an acute mooring line angle, more likely to trap debris. This principle will be applied to the development of the hybrid buoys.

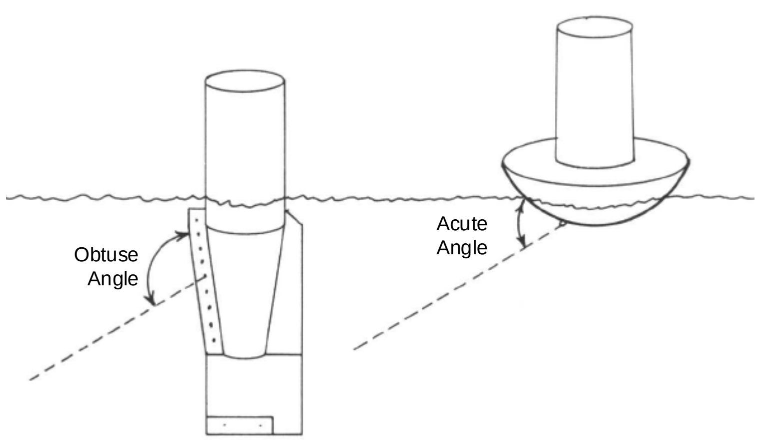


Figure 7. Standard buoy hull vs. fast hemispherical buoy hull and mooring angle.

4.2 Existing Designs (References 18 and 19)

An alternative to the steel, foam, and plastic material used in the buoys surveyed in the Worldwide Technology Survey, Section 4.1.1, ionomer and polyethylene foams are being used in new buoy designs. Gilman Corporation and Tideland Signal Corporation utilized these materials to develop buoys equivalent to the USCG 4th Class, 6th Class, and spar buoys.

The buoys were compared utilizing the same criteria as seen in Section 4.1.1, including dimensions, features, material, and additional performance characteristics. The foam river and spar buoys are listed in Table 5, Table 6, and Table 7 and figures that show the buoy configurations are in APPENDIX A. The tables list the buoys and the characteristics that were considered relevant to the evaluation.

Table 5. 6th Class foam river buoys and characteristics.

6th Class Foam Buoys	Type - Name	Location	Weight (lbs.)	Material	Current (Kts)	Visibility (Nmi)	Radar (Nmi)	Diameter (ft.)	Length (ft.)
	6-CFR	Gilman	65	Foam	2.5	1.0	0.4	1.67	5.50
	6-NFR	Gilman	65	Foam	2.5	1.0	0.4	1.75	5.50

Table 6. 4th Class foam river buoys and characteristics.

4th Class Foam Buoys	Type - Name	Location	Weight (lbs.)	Material	Current (Kts)	Visibility (Nmi)	Radar (Nmi)	Diameter (ft.)	Length (ft.)
	4 CFR	Gilman	195	Foam	5.0	1.4	0.75	3.33	8.08
	4 NFR	Gilman	180	Foam	5.0	1.4	0.75	3.33	8.08
	FW-CFR	Gilman	200	Foam	8.0	1.0	0.5	3.33	7.97
	FW-NFR	Gilman	195	Foam	8.0	1.0	0.5	3.33	7.97
	SB-104	Tideland	100	Foam	8.0	1.5	2.0	2.50	6.66

Table 7. Foam spar buoys and characteristics.

Spar Buoys	Type - Name	Location	Weight (lbs.)	Material	Current (Kts)	Visibility (Nmi)	Radar (Nmi)	Diameter (ft.)	Length (ft.)
	SB-60	Tideland	210	Foam	4.0	4.0	2.0	1.98	13.42
	SB-30	Tideland	136	Foam	2.0	1.7	0.5	1.17	7.08

4.3 Buoy Characteristic Evaluations

Once all the candidate buoys and designs were identified, further investigation and comparison was performed using the existing data to determine which of the candidate buoys had the potential to offer improved performance for the specific criteria over the existing 4th Class and 6th Class buoys. No tests were performed during this effort. Comparison of the criteria to the existing buoy data is described in this section.

The new design and spar buoys were added to the list existing buoys for an overall comparison of the available existing technology. The buoys were evaluated using weighting factors based on the relative importance of the criteria and based on USCG experience. The buoys with minimal qualifications were evaluated to determine if any lessons could be learned and design considerations could be used.

The criteria and their weighting factors are:

- Visibility 5, maintain existing capabilities
- Radar range 5, maintain existing capabilities
- Weight 4, within existing handing system capabilities

- Current 3, handle either fast or pooled water
- Diameter 2, within existing handing system capabilities
- Length 1, within existing handing system capabilities

These factors provide a rating that is based 50 percent on service to the waterway user and 50 percent on WLR handling. No attempt was made to evaluate service life, as this would have been based largely on manufacturers' claims but will be considered later. Utilizing the existing 4th Class and 6th Class buoys as bench marks, the candidate buoys shown in Table 2, Table 3, Table 4, Table 5, Table 6, and Table 7 were given the following ratings:

- Greatly Exceeded 4
- Improved 3
- Same as existing 2
- Underperformed 1
- Deficient 0

The total score for each buoy was determined by multiplying the rating by the weighting factor. The buoy candidates were then sorted by score and evaluated for the overall buoy or the specific characteristic with better analytical characteristics than the 4^{th} Class and 6^{th} Class buoy. The spar buoy comparison did not use a relative scale as the river buoys had used because there was no qualified USCG baseline. The comparison results for the buoys can be seen in Table 8, Table 9, and Table 10 and the concluding information in Section 4.4.

Table 8. Buoy evaluation: 6^{th} Class buoys.

		Visibility	Radar	Weight	Current	Diameter	Length	
	Buoy \ W.F.	5	5	4	3	2	1	Total
6th Class Buoys	Inland Unlighted STD	2.5	2	3	2.5	0.5	2	45
	FA-2015	2	3	2	2	2	2	45
	FA-2016	2	3	2	2	2	2	45
	6-CFR	2	1	4	2	1.5	4	44
	6-NFR	2	1	4	2	1.5	4	44
	FA-2010	3	4	0	2.5	0	0	42.5
	FA-2011	3	4	0	2.5	0	0	42.5
	6 CR	2	2	2	2	2	2	40
	6 NR	2	2	2	2	2	2	40
	CB-100	0	1	4	4	1.5	4	40
	FA-1001	3	3.5	0	2.5	0	0	40
	FA-2008	2.5	3.5	0	2.5	0	2.5	40
	FA-2009	2.5	3.5	0	2.5	0	2.5	40

Table 9. Buoy evaluation: 4th Class buoys.

4th Class Buoys		Visibility	Radar	Weight	Current	Diameter	Length	
	Buoy \ W.F.	5	5	4	3	2	1	Total
	SB-104	2	2.5	4	4	1.5	4	57.5
	FW-CFR	1.5	0.5	4	4	0.5	3.5	42.5
	FW-NFR	1.5	0.5	4	4	0.5	3.5	42.5
	FA-2013	2	2	2.5	1.5	2.5	2.5	42
	FA-2012	2	2	2.5	1.5	2.5	2.5	42
	4 CFR	2	1	4	2	0.5	3.5	41.5
	4 NFR	2	1	4	2	0.5	3.5	41.5
	4 CR	2	2	2	2	2	2	40
	4 NR	2	2	2	2	2	2	40
	CP-2800 - Catamaran	0	0	0	0	0	0	0
	FA-2014 - Catamaran	0	0	0	0	0	0	0

Table 10. Evaluation of spar buoys.

Spar Buoys		Visibility	Radar	Weight	Current	Diameter	Length	
	Buoy \ W.F.	5	5	4	3	2	1	Total
	SB-60	4	2.5	1.5	4	1	1	53.5
	SB-30	2	1.5	2	3	3	4	44.5
	FA-3006 0.6m Short	2	4	0.5	3	0	1	42
	FA-3005 0.6m	2	4	0	4	0	0	42
	FA-3007 0.3m, Ottawa	1	3	2	0	3	3.5	37.5
	90/160 Plastic	1	0	4	0	4	3	32
	FA-3008 Vari. Buoy.	1	0	3.5	0	4	3	30
	50/120 Pastic	0	0	4	0	4	3	27
	160 mm x 6 m Plastic	1	0	3	0	4	0	25
	225 mm x 7 m Plastic	2	0	2	0	3.5	0	25
	Selco Type 4	2	0	2.5	0	2	0	24
	Selco Type 5	1	0	2.5	0	2	1	20

4.4 Buoy Characteristics Conclusions

None of the existing buoy designs meet all of the criteria that could improve buoy life for pooled or fast waters. But this analysis identified potential existing buoys, eliminated some designs and generated ideas for the best characteristics for a more acceptable solution. As noted below, many of the individual characteristics could be adopted and used for a new design that could increase service life.

4.4.1 Pooled Water Buoys

Based on the results shown in Table 8, the 6th Class buoy candidates that showed the best potential performance and individual characteristics are the German buoy Inland Unlighted STD, Canadian buoys FA-2015 and FA-2016, and Gilman foam 6th Class buoys. Their specific superior characteristics are as follows.

- German Inland Unlighted STD buoy scored well with the visibility, weight, and current criteria, but was eliminated as a candidate because the diameter is not compatible with the WLR's existing handling and stowage hardware.

- Canadian buoys have characteristics that appear to do well under nominal daytime visibility and radar range due to their size, but are generally too heavy except for the two designs that are similar to the existing USCG 6th Class river buoys.
- The Gilman 6th Class buoys appear to be excellent candidates because of their size compatibility with the existing technology as well as their material being resistant to discoloration and damage from collision. The foam material also makes them approximately 60 percent lighter than the existing 6th Class buoy. The visibility was equal to the existing 6th Class buoy, but radar range was slightly less than that of the existing 6th Class radar buoy. It is not clear how well the buoy holds up to debris.

An alternative for standard 6th Class river buoys would be the use of spar buoys. Based on the available data, spar buoy comparison results can be seen in Table 10. Data regarding the current which they can handle was not available for all spar buoys; however, 6th Class buoys are used in pooled water where they do not need to handle high currents. Based on the results, the buoys with the best characteristics are Tideland SB-60 and SB-30 and Canadian FA-3005, FA-3006, and USA SF-5. Their specific characteristics are as follows.

- Tideland SB-60 had one of the best capabilities to handle currents up to a maximum of 4 knots. The nominal daytime visibility is the best of the compared buoys and the radar range greatly exceeds the typical standard buoy characteristics. However, to obtain maximum buoyancy, the overall length far exceeds that of the standard buoys.
- Tideland SB-30 daytime visibility and radar range are equivalent to the existing 6th Class river buoy. The ability to handle currents underperforms the existing 6th Class. The overall size is smaller in diameter, but larger in overall length.
- Canadian FA-3005 and FA-3006 and USA SF-5 have much better radar range than existing buoys due to their greater overall size compared to the other candidates. The overall size also contributed to a larger weight and greater handling needs.

Based on these results, it can be concluded that the Gilman 6th Class foam buoys would present a feasible option as a standard river buoy. The buoy's deficiency in radar range can be addressed during the detailed conceptual design phase and will require collaboration with Gilman Corp. to determine the best course of action. Due to the nature of pooled water, its average current handling ability does not negatively contribute to its rating. Buoys that can handle higher currents are generally larger, but do not present significant improvements. The use of spar buoys is still a viable option based on the overall characteristics of the Tideland SB-30. The performance characteristics are either similar or improved compared to the existing 6th Class buoys. Improvements in radar range can be researched and collaborated with Tideland Signal Corporation if this buoy is selected for future efforts.

4.4.1 Fast Water Buoys

Based on the results shown in Table 9, the 4th Class buoy candidates that showed the best analytical performance and individual characteristics are the Tideland SB-104, Canadian FA-2012 and FA-2013, and USA 4CR and 4NR. The Gilman 4CFR, 4NFR, FW-CFR, and FW-NFR were also included even though they did not score as well, but present superior weight and damage resistance characteristics. As seen in Table 9, the Tideland SB-104 outscored the other buoys by a significant margin. This outcome resulted in it being the chief candidate for further investigation for fast-flowing water buoys. The only characteristic where this buoy did not meet the criteria was the diameter of the buoy, which may affect handling. Upon further review, the difference compared to the existing 4th Class buoy is only 3 in. Improvements to the

overall size are not considered at this time despite their impact on visibility, stowage, and handling, but will be discussed when debris shedding ability is investigated. Additional information regarding debris shedding is provided in Section 4.1.3, which will be used to evaluate the SB-104. Spar buoys should not be used for fast-flowing water because their smaller diameter is more likely to accumulate debris.

5 BUOY SYSTEM DESIGN

5.1 Buoy Design and Analytical Performance

5.1.1 Goals and Constraints

The next step was to incorporate the information previously learned into a new buoy design. The design of the new buoy needs to exceed the performance characteristics of the existing USCG 4th Class buoys in pooled and fast-flowing waters and existing 6th Class buoys in pooled waters. Specific goals and constraints were applied during the design phase to make sure the conceptual design meet the design requirements, including:

- Goals:
  - The service life of the buoy had to be equal or better than the existing, affecting the life cycle cost compared to the existing USCG buoys.
  - Improved survivability of the buoy from damage from collision, debris accumulation in fast-flowing waters, and loss due to diving.
  - Improved handling by allowing for easier deployment and retrieval during operations. The handling is also affected by the diameter and overall length of the hybrid design.
  - Increase the visibility of the hybrid buoy allowing for greater spacing; therefore, reducing the number of required buoys.
  - Reducing the drag or drag affects of the buoy on mooring lines.
- Constraints:
  - The hybrid buoy must be serviceable by existing WLRs or minimally impact the operations, which includes the buoy handling by the crane and on-deck storage and space requirements.
  - The constructability and maintenance of the buoy must be easily achieved or minimally impact the training and equipment required.
  - The life cycle cost must be improved over the existing buoys.

5.1.2 Design Methodology

The hybrid buoy design was developed by investigating specific areas that had the potential for improvement including ionomer foam and an underwater shape to reduce the drag and utilize the effective methods of shedding debris. Several spreadsheets were developed to individually and collectively calculate the necessary parameters to analyze the buoy performance characteristics, including:

- Hydrostatics:
  - Utilizing the cross-sectional area and applying the Simpson Rule to three section intervals, the volume was determined and totaled to calculate the available displacement and buoyancy.
  - The metacentric height, center of buoyancy, moment of inertia, and righting arm were calculated to determine the stability of the buoy at 0 knots, no mooring and submergence threshold.
- Catenary length and mooring line angle:

- The catenary length at each current was calculated to determine the additional weight acting on the buoy. To determine the length, the following equation was applied:
  - **Length = $\sqrt{(2 \times Y \times C + Y^2)}$** (Reference 14)
    - Y = Total vertical distance
    - C = Parameter = H/w_{ml}
    - H = Required holding power = D
    - w_{ml} = Weight per foot of the mooring line
- Hydrodynamic drag:
  - Buoy drag was calculated using the fluid dynamic drag equation:
    - **$D = \frac{1}{2} \rho \mu^2 C_D A$** (Reference 15)
      - ρ = Density of the fluid
      - μ = Relative velocity of fluid
      - C_D = Drag coefficient (Reference 16)
      - A = Frontal area of submerged volume
  - The tension was calculated in the mooring line by dividing the total tension into axial components (Figure 8):
    - $\Sigma T_x = D - T \cos\theta = 0$
    - $\Sigma T_y = W_{ml} + D_y - T \sin\theta = 0$
      - D = Drag on the buoy applied in to x-axis
      - T = Tension in the mooring line
      - B = Available buoyancy of the buoy
      - W_{ml} = Total weight of the catenary
      - D_y = Vertical component of the buoy drag
        - Only applied at full catenary length
  - The downward force acting on the buoy was the sum of the tension in the y-axis and the weight of the buoy
- Hybrid design weight and center of gravity (CG):

  During the development of the hybrid design for both 4th Class and 6th Class buoys, the design was decomposed into individual components and the CG and weight for each component was determined. The collective CG and weight was then calculated for the overall design and used during stability and drag tests.
- Assumptions:
  - Wind effect is negligible.
  - Uniform current velocity along the buoy profile.
  - The sinker is fixed to the bottom.
  - Only a two-dimensional analysis is required.
  - The buoy remained upright.
  - The debris drag is negligible.
  - Buoy hull is cylindrical.
  - Mooring line length is maximum at 90 ft.
  - Mooring line drag is negligible.
  - Mooring depth is set at 40 ft.
  - Mooring line is standard USCG ½-in. chain (Reference 17).

Using the above equations and conditions, the design development was evaluated solely on a theoretical basis with generalized equations. The downward force was directly proportional to the draft of the buoy, which was used to calculate the frontal area of the drag. Allowing for circular iteration within the

spreadsheet, the submerged volume, draft, frontal area, and drag were calculated over a 10,000 iteration cycle to converge on a draft at each current applied. The draft, tension components, drag components, and mooring line angle are dependent functions of the calculated buoy weight, water depth, mooring line size and weight, scope, and current velocity (Reference 3). The design axis orientation is shown in Figure 8.

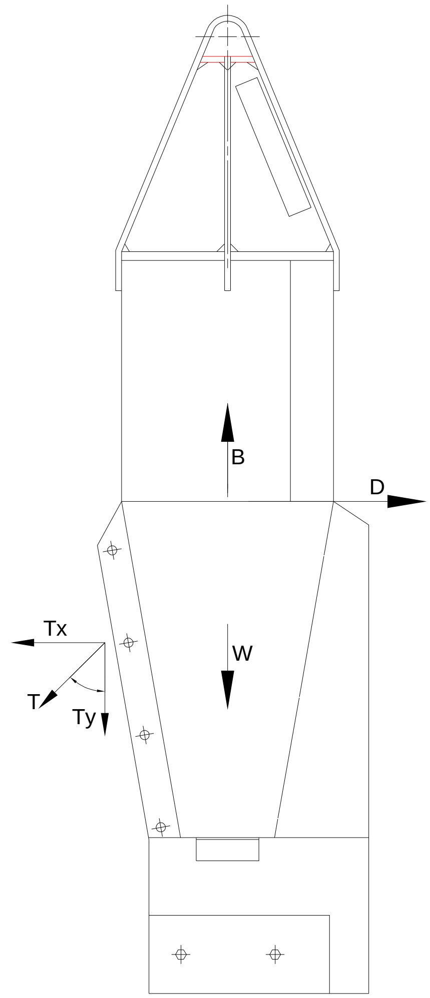


Figure 8. Buoy design axis orientation (Reference 4).

5.2 Preliminary Design

The design of the buoys are hybrid concepts of the existing 4th Class and 6th Class buoys utilizing the ionomer foam construction and steel components for weight and performance requirements. The diameter and footprint of the buoy is the same as the existing, but the overall length has been altered to either maintain or outperform the existing buoy designs. Both hybrid designs use a steel mooring and rudder assembly similar to the existing buoys, but with modifications for stability, weight, and constructability.

Each buoy is constructed of 3.5 lb/ft^3 ionomer foam, similar to that of Gilman Corporation (Reference 18) wrapped around a steel center pipe running along the full length. The center pipe, mooring, and rudder assembly form the steel member of the design and will be constructed as one solid piece. The foam body will slide onto the steel pipe and rest on a support plate/gusset for the rudder fin. The foam will be secured to the pipe via a threaded bolt that will attach the lifting staple at the top of the pipe, centered on the buoy.

Internal radar targets will be used as the radar signal source. Schematic drawings of the 4th Class and 6th Class buoys can be seen in Sections 5.2.1 and 5.2.2, respectively, with their dimensions and construction specifications. The can and nun daymark design has been developed for both class sizes.

5.2.1 4th Class Hybrid

As mentioned in Section 5.2, the basic design is the same as the existing, but the 4th Class Hybrid buoy allows for an attachable extended fin depending on conditions it will be used in as per the recommendations extracted from the USCGA concept design (Section 0). The design of the extendable fin will need to be developed during the detail design phase to also incorporate changes to the CG and affect the required counterweight. This modular rudder allows for the buoy to be used in both fast-flowing and pooled waters. Figure 9 and Figure 10 show the schematic drawing of the 4th Class Hybrid design with basic rudder fin design.

5.2.2 6th Class Hybrid

As mentioned in Section 5.2, the basic design is the same as the existing. The 6th Class Hybrid is designed for pooled waters only. Figure 11 and Figure 12 show for the schematic drawing of the 6th Class Hybrid design with basic rudder fin design.

5.3 Analyses

The candidate buoys selected in Section 4.4 have been compared to the hybrid design using the following performance parameters:

- Maximum current handling
- Mooring line tension
- Freeboard at maximum current
- Submergence current
- Drag forces

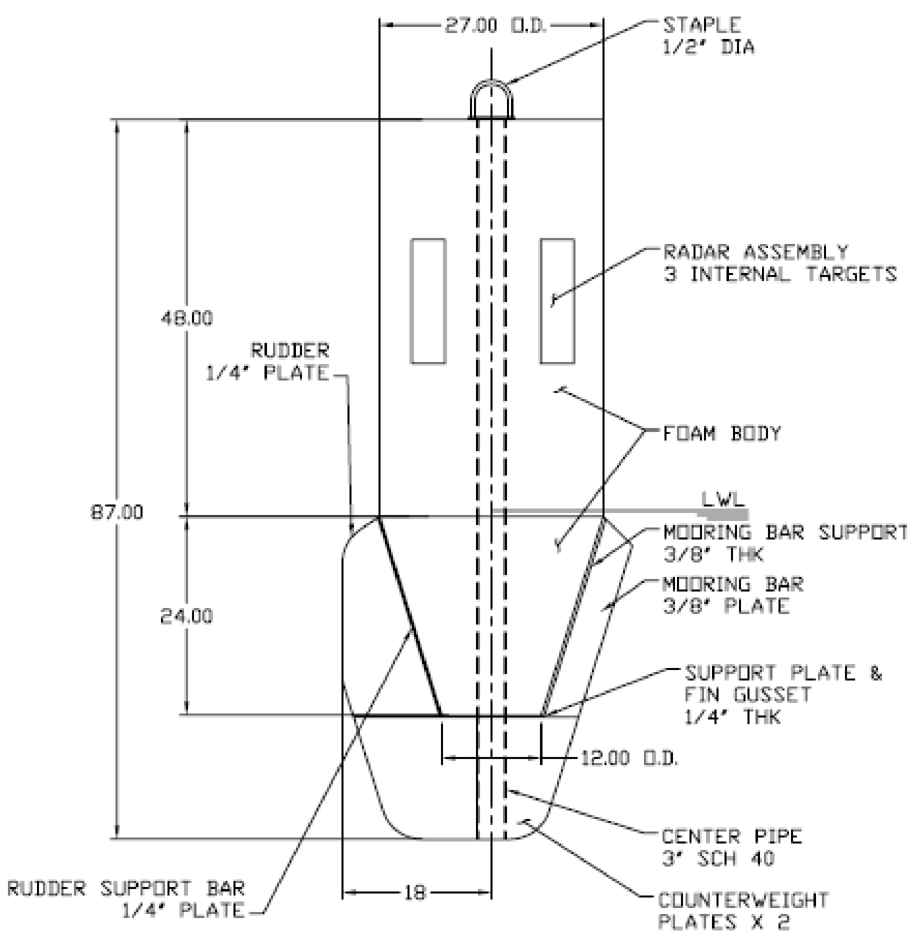


Figure 9. 4th Class hybrid buoy: can daymark.

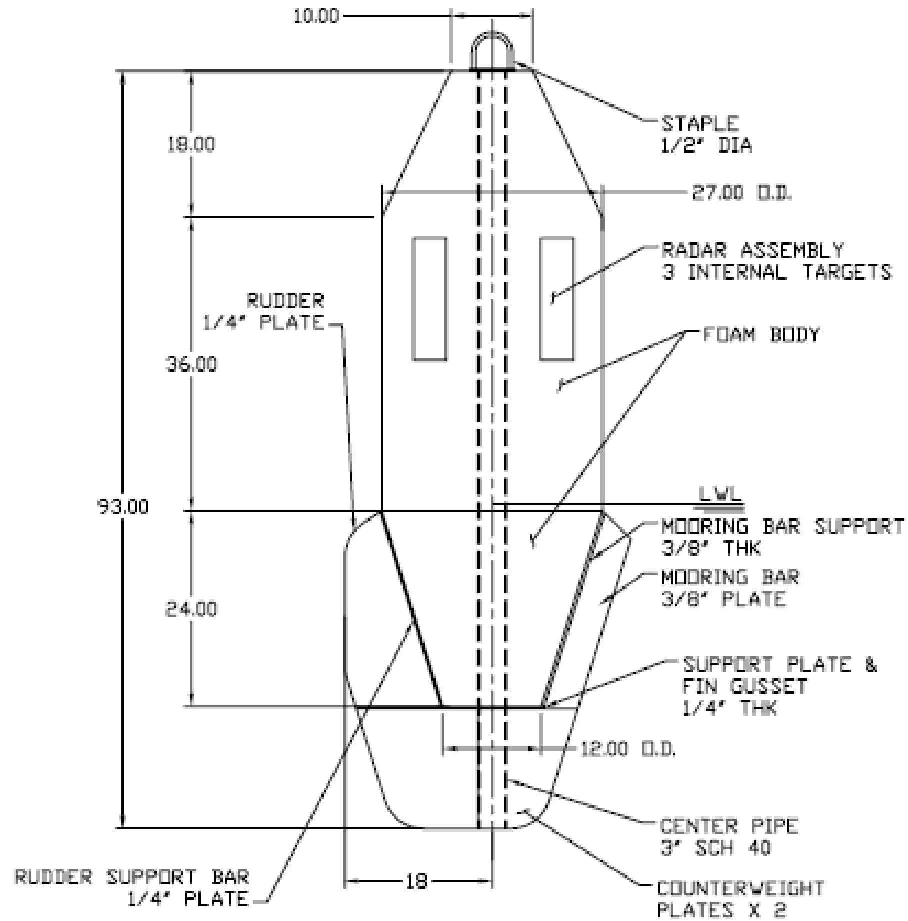


Figure 10. 4th Class hybrid buoy: nun daymark.

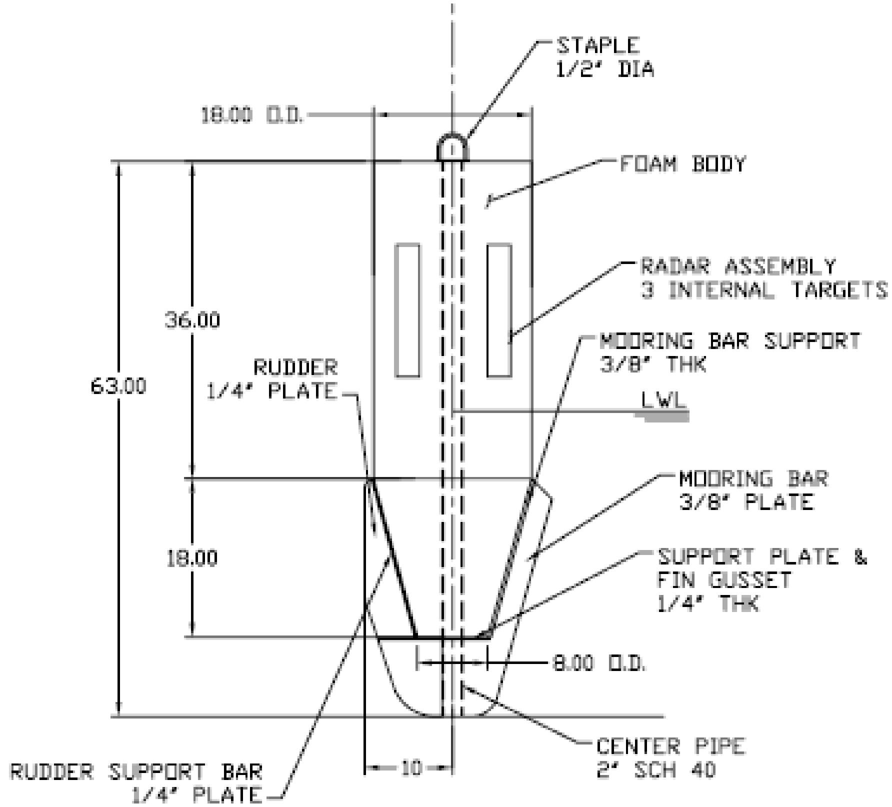


Figure 11. 6th Class hybrid buoy: can daymark.

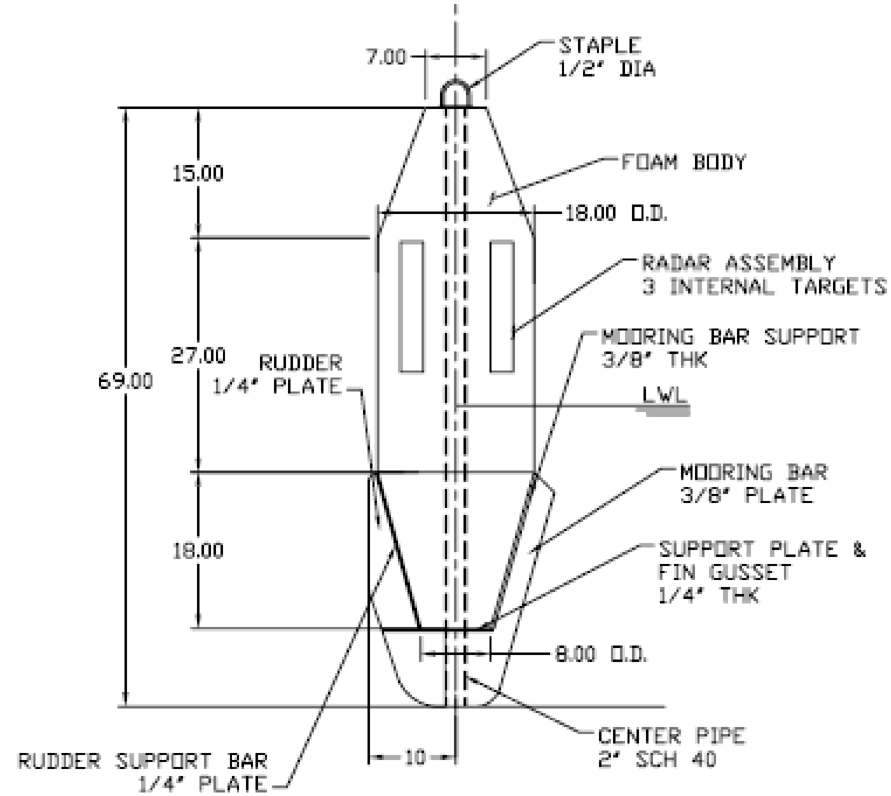


Figure 12. 6th Class hybrid buoy: nun daymark.

5.3.1 Drag Forces

Using the formulas shown in Section 5.1.2, the drag forces of the candidates buoys compared to the freeboard and submergence velocity and are shown in Appendix C.

5.3.2 Mooring Line Forces

Using the formulas shown in Section 5.1.2, the mooring line tension of the candidate buoys versus the current velocity has been graphically displayed in Figure 13 and Figure 14. Data from Reference 3 has been entered as comparison under data line "Colburn Report" for both 4th Class and 6th Class buoys. Reference 3 data was taken from actual field evaluation, which explains the discrepancy in data points. Buoy inclination and oscillation allow the buoy to prevent submergence compared to an assumption of upright orientation at all currents, constantly increasing the frontal area of the buoy drag.

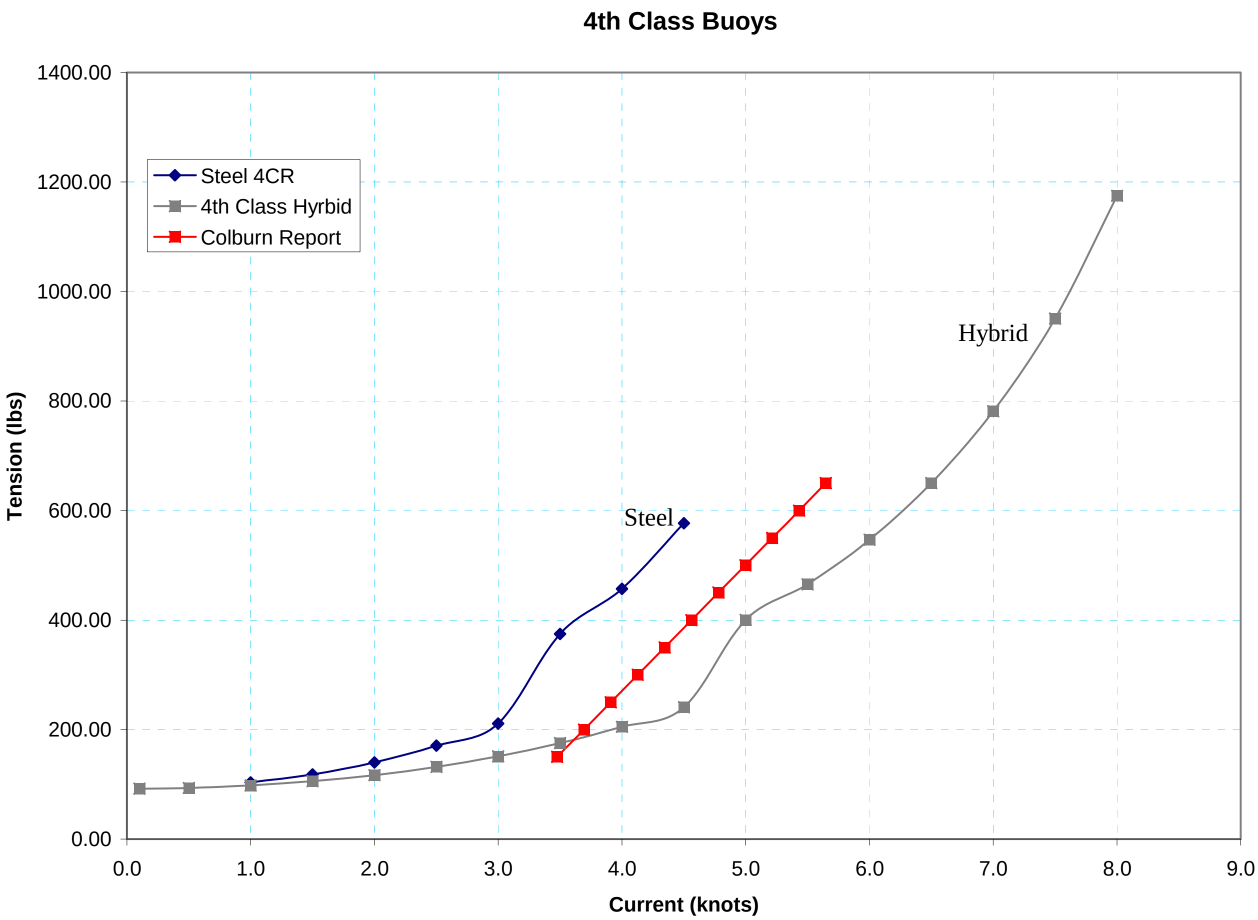


Figure 13. 4th Class buoy comparison: current vs. mooring tension.

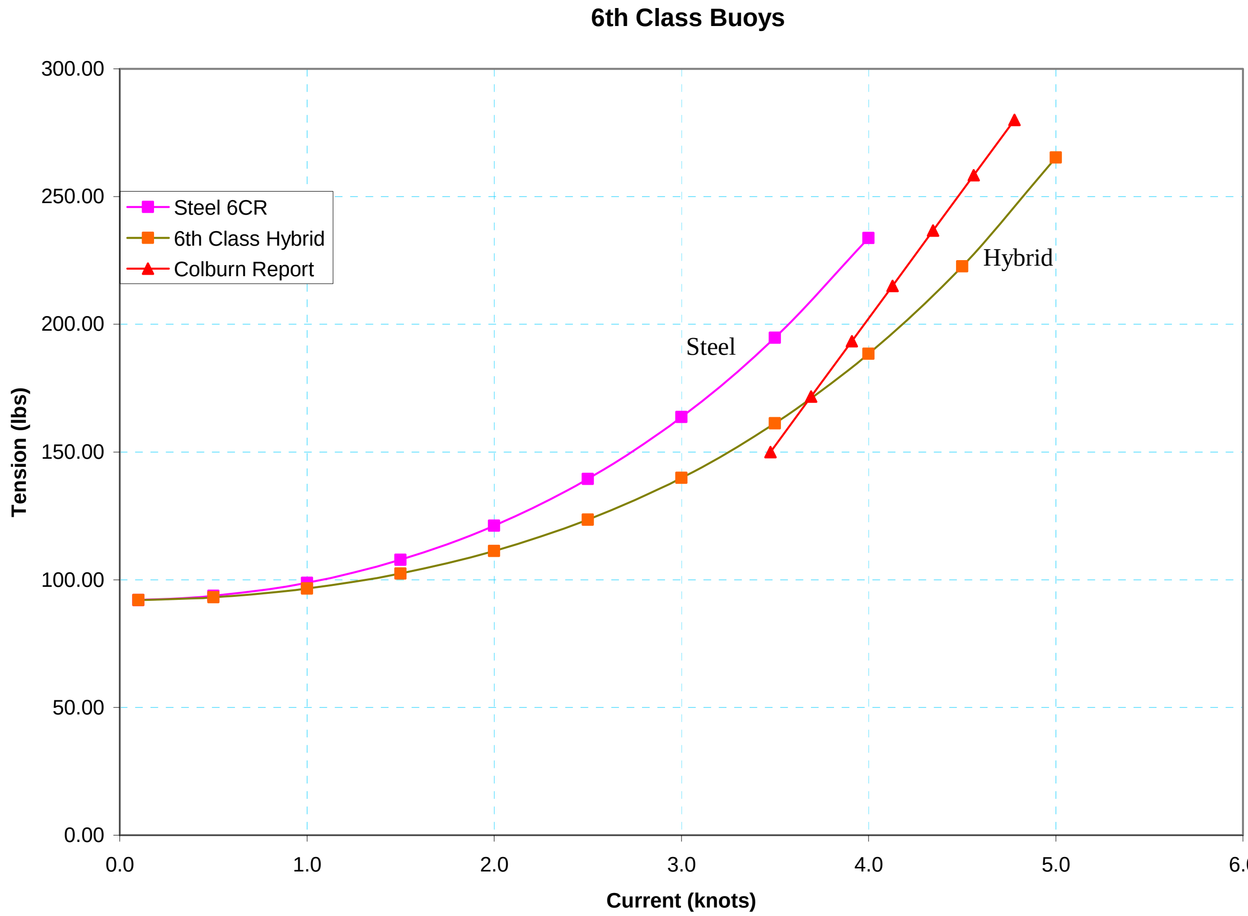


Figure 14. 6th Class buoy comparison: current vs. mooring tension.

5.3.3 Candidate Buoy Characteristics Evaluation

Using the same approach as in Section 4.3, the candidate buoys with the good characteristics listed in Section 4.4 have been compared analytically against the 4th Class and 6th Class hybrid design using the same criteria and rating system. The performance characteristics have been listed in Table 11 and Table 13 and the comparison results listed in Table 12 and Table 14. The freeboard values listed have been taken from Appendix C. from the buoy that submerged at the lowest currents for an even comparison.

Table 11. Detailed 4th Class buoy characteristics.

	Type - Name	Location	Weight (lbs.)	Material	Current (knots)	Freeboard (ft.)	Radar (Nmi)	Diameter (ft.)	Length (ft.)
4th Class Buoys									
	4 CR	USCG	465	Steel/Foam	4.5	1.4	1.5	2.25	9.25
	4 NR	USCG	470	Steel/Foam	4.5	1.4	1.5	2.25	10.44
	FA-2013	Canada	300	Steel	6.0	1.9	1.5	2.00	8.72
	FA-2012	Canada	350	Steel	6.0	1.9	1.5	2.00	8.79
	4 CFR	Gilman	195	Foam	8.0	3.7	0.75	3.33	8.08
	4 NFR	Gilman	180	Foam	8.0	3.7	0.75	3.33	8.08
	FW-CFR	Gilman	200	Foam	8.0	3.5	0.5	3.33	7.97
	FW-NFR	Gilman	195	Foam	8.0	3.5	0.5	3.33	7.97
	SB-104	Tideland	160	Foam	8.0	2.6	2.0	2.50	6.66
	4th Class Hybrid	AMSEC	230	Foam	8.0	3.1	0.75	2.25	7.25

Table 12. Detailed 4th Class buoy rating.

4th Class Buoys		Freeboard	Radar	Weight	Current	Diameter	Length	
	Buoy \ W.F.	5	5	4	3	2	1	Total
	SB-104	2.5	3	4	4	1.5	4	62.5
	4 CFR	4	1	3	4	0.5	3	53
	4 NFR	4	1	3	4	0.5	3	53
	4th Class Hybrid	3	1	2.5	4	2	3.5	49.5
	FW-CFR	3.5	0.5	3	4	0.5	3	48
	FW-NFR	3.5	0.5	3	4	0.5	3	48
	FA-2012	2	2	2.5	3	3	2.5	47.5
	FA-2013	2	2	2.5	3	3	2.5	47.5
	4 CR	2	2	2	2	2	2	40
	4 NR	2	2	2	2	2	2	40

Table 13. Detailed 6th Class buoy characteristics.

6th Class Buoys	Type - Name	Location	Weight (lbs.)	Material	Current (knots)	Freeboard (ft.)	Radar (Nmi)	Diameter (ft.)	Length (ft.)
	6-CFR	Gilman	65	Foam	5.5	1.8	0.4	1.67	5.50
	6-NFR	Gilman	65	Foam	5.5	1.8	0.4	1.75	5.50
	SB-30	Tideland	136	Foam	2.0	0.7	0.5	1.17	7.08
	6 CR	USCG	160	Steel/Foam	3.0	2.0	1.0	1.50	7.25
	6th Class Hybrid	AMSEC	77	Foam	4.5	2.1	0.4	1.50	5.25

Table 14. Detailed 6th Class buoy rating.

6th Class Buoys		Freeboard	Radar	Weight	Current	Diameter	Length	
	Buoy \ W.F.	5	5	4	3	2	1	Total
	6th Class Hybrid	3	1	3	3	2	4	49
	6-CFR	1.5	1	3	4	1	3.5	42
	6-NFR	1.5	1	3	4	1	3.5	42
	6 CR	2	2	2	2	2	2	40
	SB-30	0	1	2.5	1	3	3	27

5.4 Costs

5.4.1 Buoy Costs (References 8 and 9)

The cost factor did not contribute during the design phase as a major constraint; however, it was considered when determining if the new hybrid design would be an affective competitor for future missions. The cost of the buoy including the material and fabrication costs are seen in Table 15. The cost of the AMSEC hybrid buoys is assumed at 120 percent of the Gilman buoy to account for the additional steel and fabrication. The cost of the Canadian buoys is assumed as the same as the USCG river buoys because of similar shape, design, and material. Delivery costs to the WLRs are not included. The unit cost of the hybrid buoy is greater than existing, but the anticipated life cycle cost and operating performance should prove to outweigh the higher upfront cost and is shown in incremental measurements in Section 5.4.2.

Table 15. Buoy cost.

Buoy	Cost
Fast Water Buoys	
USCG 4CR	$534
Gilman 4CFR	$1,529
Gilman FWCFR	$1,201
Tideland SB-104	$2,000
Canada FA-2012	~$534
4th Class Hybrid	~$1,800
Pooled Water Buoys	
USCG 6CR	$276
Gilman 6CFR	$415
Tideland SB-30	$575
6th Class Hybrid	~$500

5.4.2 Life Cycle Costs

To determine the relative life cycle costs of the various buoy alternatives, the buoy cost, the installation cost, and the expected life of the alternative must be assumed. The actual and estimated costs for the various buoys are provided above. The operating cost of the WLRs has been given as $2,465 per hour and the time to retrieve and set a buoy has been assumed as 15 minutes (Reference 12). This results in an installation cost of $616 per buoy.

For the purposes of this study, the life cycle will be considered as 12 years to allow comparison of buoys having 2-, 3-, 4-, and 6-year lives. This means that for over a 12 year period, if the buoy life is two years, then 6 buoys need to be procured and they have to be launched 6 times. For example, the USCG 4CR buoy would cost $534 (buoy cost) plus installation ($616) for a total of $1150 for each new buoy. The total costs for providing 12 years of service for the various buoys are provided in Table 16.

In addition to the assumptions above, the following should be noted:

- The costs below do not include the purchase cost of the wire or chain mooring.
- The buoy prices do not include delivery to the WLR base.

Table 16. Twelve-year costs of buoys.

Buoy	Buoy Life			
	2 Years	3 Years	4 Years	6 Years
Fast Water Buoys				
USCG 4CR	$6,900	$4,600	$3,450	$3,532
Gilman 4CFR	$12,870	$8,580	$6,435	$5,522
Gilman FWCFR	$10,902	$7,268	$5,451	$4,866
Tideland SB-104	$15,696	$10,464	$7,848	$6,464
Canada FA-2012	$6,900	$4,600	$3,450	$3,532
4th Class Hybrid	$14,496	$9,664	$7,248	$6,064
Pooled Water Buoys				
USCG 6CR	$5,352	$3,568	$2,676	$3,016
Gilman 6CFR	$6,186	$$4,124	$3,093	$3,294
Tideland SB-30	$7,146	$4,764	$3,573	$3,614
6th Class Hybrid	$6,696	$4,464	$3,348	$3,464

From the above, it can be seen that the 12-year cost for maintaining a 4th Class USCG buoy that has to be typically replaced every 2 years will be $6,900. Using a 4th Class Hybrid, with a 6-year service life, will cost $6,064 for 12 years. The greatest potential savings might come from the use of a Gilman FWCFR, which would cost only $4,866 for 12 years; assuming a 6-year service life. Also, the table shows that it does not pay to use the more expensive buoys in locations where they are more likely to be damaged by barge tows and last only 2 years. All of the alternatives are more expensive than the existing buoy except for the Canadian buoy which is very similar to the existing CG buoy.

For the 6th Class buoys, the cost of maintaining the standard USCG buoy on station for 12 years is $5,352, assuming replacement every 2 years. The cost of a 6th Class hybrid buoy that should last 6 years would be only $3,464, resulting in a significant savings. The Gilman 6CFR buoy offers slightly better savings. Thus, the use of ionomer foam buoys can offer significant savings in locations where barge tow damage is not significant. Again, all of the alternative buoys cost more than the existing buoy.

In reviewing this data, it should be noted the assumption of 15 minutes of WLR time to install a buoy may result in installation costs that are unrealistically low. Determination of the total cost for a single WLR cycle of 1-week in/1-week out divided by the number of buoys set while underway during that cycle may provide a more realistic cost of retrieving and deploying a buoy. Increases in installation costs will make the longer lasting buoy alternatives more economical.

5.5 Mooring Lines

The USCG has been using two different systems: wire rope and steel chain, both being used over many years. Having analyzed the collected data, this report contains the results of a study on the mooring performance of chain, wire rope, and synthetic rope. In particular, the objective of this study was to assess the circumstances in which mooring systems containing wire or chain mooring have superior mooring performance to those containing synthetic rope, since preliminary investigations indicated that the advantages of synthetic rope become more apparent with deep water moorings.

5.5.1 Existing Wire Rope and Chain

For fast-water buoys, the USCG uses wire rope 1/2-in. (nominal diameter), Type 1, general purpose, class 2, 6X19 wire rope. Right regular lay, improved plow steel with polypropylene rope core, uncoated (1/2" 6X19CL PRF RPL PPC IPS BRIGHT), the wire rope has a breaking strength of 20,400 pounds.

For pooled water buoys, the USCG uses 1/2-in. chain welded open link chain, Studless Grade 1, with breaking strength of 15,000 pounds (Reference 10).

5.5.2 Synthetic Rope

Where synthetic ropes are used, it is possible to reduce mooring line weight and hence the weight of the buoy. Also, extreme line dynamic tension is reduced due to its lower tensile stiffness and corrosion resistance. This analysis investigated design, analysis, rope testing, manufacturing, handling, installation, inspection, and maintenance to integrate and provide a consistent mooring system.

Synthetic ropes are visco-elastic materials, so their stiffness characteristics are not constant and vary with the duration of load application, the load magnitude, the number of load cycles, and the frequency of load cycles. In general, synthetic mooring lines become stiffer after a long time in service.

Synthetic ropes have poorer abrasive and tension-bending fatigue characteristics than their steel wire or chain counterparts. Therefore, chain/wire segments need to be used to attach the synthetic rope to the buoy to avoid bending and fatigue at the ends. The upper termination of the synthetic rope should be located well below the waterline so that all the rope remains submerged. The main reason is to reduce the likelihood of any rope damage from surface vessel activity and protect from ultraviolet (UV) effects. Lower synthetic rope termination chain/wire segments need to be used at the lower termination of the synthetic rope. Adequate clearances above the bottom should be provided.

The rope manufacturer should be responsible for developing the rope design, including terminations; documenting the design details; then following this design when making prototype and production ropes. The manufacturing specification should completely describe the rope construction and parameters, and the steps and processes used in making the rope. This specification documents all the important parameters of the rope making process appropriate for the particular type of rope, along with nominal values and allowable variations for these parameters. The specification describes the rope termination and its method of assembly or application as appropriate (spliced, potted socket, and wedged socket terminations). It documents nominal values and allowable variations for all termination design and application parameters appropriate for the particular type of rope and the yarn tests. The yarn is tested for breaking strength (tenacity) and load-extension characteristics. Yarn-on-yarn abrasion was found to be an important factor in the fatigue performance of nylon and polyester ropes and may also be a factor in aramid ropes. Breaking strength is very important.

The torque and rotation characteristics of a synthetic rope are of concern if that rope will be used in series with a wire rope, either during installation or in-service. Also, splices generally have different torque characteristics than the body of the rope, and the resulting rotation can sometimes damage the rope. To prevent these problems, any synthetic mooring should include swivels to allow free rotation of the rope. Another issue to consider is tension-tension cyclic performance. The long-term fatigue performance of synthetic ropes used in moorings is a special concern. While it is possible for the rope to serve for 20 years or more, it is not practical to conduct fatigue testing at realistic loads on full-size ropes to demonstrate such performance. The fatigue test included in the ABS Guidance Notes (Reference 20) demonstrates that the synthetic rope has fatigue properties at least as good as the 6-strand multi-strand-wire.

Also of concern is rope production and quality assurance. The rope manufacturer is responsible for adhering to the yarn, manufacturing, and termination specifications that were developed for the rope design. Handling and installation should be considered as part of the planning of deployment and installation techniques. External abrasion, rope torsional properties, tension-relaxation properties, heat build-up, and internal abrasion must be considered and may require the following: handling equipment and work surfaces which have appropriate finishes; steel end terminations to be of suitable nonprotruding construction; segregated spooling from steel wire components; use of special grips, etc.; external marking on jacket so that rope twist can be monitored; torsionally compatible mooring components by testing and/or calculation; a limiting speed on synthetic rope deployment; waterspray during deployment; and a rope storage location remote from heat (i.e., welding and sunlight, etc.) and from any foreign particle presence. Once the synthetic mooring system has been placed, a regular inspection program may be required.

5.5.3 Mooring Line Conclusion

Synthetic ropes are often used as mooring lines for deep water systems because of their light weight; however, synthetic ropes have poorer abrasive and tension-bending fatigue characteristics than their steel wire or chain counterparts. Chafing is by far the most common cause of rope failure and it is surprisingly

difficult to prevent. Anti-chafing gear is essential wherever the rope is likely to be abraded and frequent careful inspection is imperative. Danger areas are where it is connected to a buoy or swivel and, of course, where it can rub on the bottom.

Synthetic rope strength is known to be adversely affected by the ingress of foreign particles such as sand. It is more likely that particle ingress occurs at low tensions because under high tensions, the rope compacts, reducing free spaces in the rope construction. The wear induced by the particles may result in mooring losses. Jacketing the rope can prevent ingress but add to the cost. At high stresses, plastic flow of fibers can occur resulting in premature failure. One of the difficulties with rope is establishing the correct size for the application. The problems of calculating forces exerted on a mooring have already been discussed. With chain, provided that there is sufficient scope and weight, the catenary curve will absorb whatever loads are likely to be generated. A rope that is too light can create this curve; selecting a rope that is too strong may cause the anchor to be pulled loose before it stretches enough to get any spring action. Conversely, if a rope is too weak, it could stretch to breaking point causing the loss of the buoy.

Synthetic ropes have many advantages in deeper water moorings, but their unique properties must be accounted for in the mooring system design process, where the moorings rely primarily on rope elasticity for restoration forces. In this particular application and because of the scale of the system, this advantage does not make a difference against the use of conventional steel chain or wire rope which has proven reliability. The scope is a critical factor which affects holding power and the angle of the pull on the sinker. However the scope is much more difficult to ensure when anchoring with rope. To achieve the desired angle of pull, it is common practice to use a length of chain between the anchor and the rope. This has the added advantage of lessening the likelihood of the rope chafing on the bottom but, even with this, greater scope is required. As a rough guide, such an arrangement needs a 5 to 1 minimum scope for rope compared to 3 to 1 for chain. The weight of chain hanging from a buoy is more likely to keep the buoy on station.

Rope connections also present some problems in joining it to other components. Even a skillfully executed eyesplice will weaken a nylon rope by up to 15 percent, whereas a badly made one, like most knots, will effectively halve its strength. Other ropes will present other difficulties; some modern synthetic types, for example, are particularly “slippery,” so knots and splices are more suspect. Laid ropes may be spliced to chain quite easily or can be fitted with thimbles to facilitate the use of shackles, but braided or plaited ropes are more difficult to work with.

Chain of course has its drawbacks too. It will wear, rust, and is generally awkward, heavy, and dirty to handle. In its favor are the facts that it stows easily, and it offers the overriding benefit of distributed weight. Finally, it does not deteriorate in sunlight, so maintenance can be safely limited to periodic visual inspections. All things considered, chain and wire rope remain superior for this application.

5.6 Sinkers

The existing sinker construction using concrete and steel lifting/mooring eye loops should remain. Utilizing the hybrid design mooring and drag forces, it can be concluded that the holding power can be reduced. This reduction will yield a smaller sinker, which will be easier to handle and reduce chafing on the attachment point, decreasing wear. A smaller sinker will also reduce the area that the chain is chafing against, increasing chain life. The steel eye loop attachment should remain recessed within the concrete body for easier handling and stowage on the WLR.

6 CONCLUSIONS AND RECOMMENDATIONS

This effort has identified some options for buoys in both pooled and fast waters that have the potential to increase the life of a buoy by increasing many of its individual characteristics. No existing buoys met all of the criteria so new hybrid buoys designs have been proposed. Since this is an analytical study and no tests were performed, additional analysis and testing will be needed to confirm the performance characteristics and the actual costs of a new buoy and confirm its capability with existing handling systems.

6.1 Fast Water Operations

Using the results from the comparison done in Section 5.3.3, 1, the Tideland SB-104 and AMSEC 4th Class Hybrid design were top-performing candidates, based on the data. The Tideland SB-104 has been designed to reduce drag and minimally impact the mooring system; however, its design is likely to collect debris, similar to the existing USCG fast-flowing waters hemispherical buoy because of its acute mooring angle. The design of the buoy is also not compatible with the existing WLRs because of the larger diameter and non-uniform base. These negative features do not meet the goals and constraints set in Section 5.1.1; therefore, they prevent it from being selected. The Gilman foam 4th Class buoy has characteristics that indicate it may perform very well; however, the large hull diameter, which provides greater buoyancy, also reduces the amount of buoys capable of being stored on deck and increases the handling difficulty.

The AMSEC 4th Class Hybrid design does meet many of the goals and constraints; and its characteristics are better than the other candidate buoys based on the following:

- Ionomer foam reduces the total weight, significantly below that of the existing USCG 4th Class buoy. The foam construction should also make the buoy more resistant to permanent damage from collision, a contributing factor in buoy loss, as mentioned in Section 2.2. Ionomer foam also features integrated buoy coloring, thereby reducing discoloration and fading with greater resistance to environmental factors.
- The internal radar reflector assembly may reduce downtime by not requiring the replacement of the steel assembly when damaged; however, it does reduce the radar reflectivity range.
- Decreased weight provides greater freeboard than the existing aid, increasing the daytime visibility. The design and draft also provide sufficient depth for the mooring line to prevent debris accumulation on the hull of the buoy.
- The underwater shape reduces the frontal area, and consequently drag, allowing for use in greater currents.
- The rudder design reduces vortices to prevent oscillation and reduces drag on the mooring line.

6.2 Pooled Water Operations

Using the results from the comparison done in Section 5.3.3, and Table 14, the AMSEC 4th Class Hybrid and 6th Class Hybrid designs meet many of the goals and constraints; and their characteristics appear to be better than the candidate buoys based on the following:

- Ionomer foam reduces the total weight, significantly below the existing USCG 4th and 6th Class buoy. The foam construction should also make the buoys more resistant to permanent damage from collision, a contributing factor in buoy loss as mentioned in Section 2.2. Ionomer foam also features integrated buoy coloring, thereby reducing discoloration and fading with greater resistance to environmental factors.

- The internal radar reflector assembly may reduce downtime by not requiring the replacement of the steel assembly when damaged; however, it does reduce the radar reflectivity range.
- Decreased weight provides greater freeboard than the existing, increasing the daytime visibility.
- The underwater shape reduces the frontal area and consequently drag, allowing for use in greater currents.
- Similar diameter to existing buoys, allowing for compatible handling and stowage with the WLRs equipment and deck spacing.

6.3 Recommendations for Future Studies

Future studies and tests for the Western Rivers Inland buoy system should include the impact that the new hybrid design has on the existing WLR fleet. Based on physical dimensions and configuration of the hybrid design, there should be no impact to the deck stowage and the number of buoys in the WLR inventory. The material and construction allow for the reduction in weight to ease the handling operation and has potential to reduce the manning required per buoy deployment and maintenance cycle. The color-integrated foam and modular assembly will allow buoy repair to be done at the WLR base. Additional equipment could be utilized to perform patchwork and minor hull repair aboard the tender, but would not be necessary if the modular components are stowed aboard.

A future field test will be needed to determine the actual life cycle of the buoy and mooring system to determine a maintenance schedule and yearly cost of each buoy. Based on material assumptions, the buoys should maintain a minimum of a 3-year life cycle, with reduced strain on the mooring line, reducing the need for frequent replacement. Periodic measurement should be performed to determine the actual chain wear from the new buoy loads.

The hybrid buoys offer greater visibility and radar reflectivity range at greater currents, which will permit different configuration of buoy locations. Buoys could permit greater station spacing between each buoy; therefore, reducing the number of required buoys or allow for more efficient operations. The channel demarcation may be reconfigured with the reduced number of required buoys.

It is feasible that cost-effective gains could be made for buoys in pooled conditions; but it is not clear if this is the case for fast waters. The gains in pooled water could be made through increased service life and less maintenance; and thus, decreased tender time for each buoy, so efforts should be focused in that area. More analysis of the loss factors are needed in fast water conditions (i.e., frequency of getting hit, frequency of getting tangled by debris, etc.) before any recommendation can be made on further buoy design analysis and testing.

7 REFERENCES

1. Systems Planning and Analysis, Inc., *Mission Analysis Report for Coast Guard Western Rivers Aids to Navigation Assets*, 28 March 2008
2. CG-D-05-92, Daidola JC., et al, *Worldwide Buoy Technology Survey*, M. Rosenblatt & Son, USCG Research and Development Center, February 1991
3. CG-D-5-77 *Lightweight Low Drag Fast Water Buoys*, US Department of Transportation, USCG Office of Research and Development, December 1976
4. 1/c Cart C, et al *Fast Water Buoy Design*, USCGA, 4 May 2006
5. Project 2510 – Buoy Hulls *Debris Shedding Test Report*, January 1974
6. CG-D-58-76 *Swift-Running Rivers Work Group Formal Reports Pertaining to Investigations and Analyses Performed Between June 1974 and August 1975*, US Department of Transportation, USCG Office of Research and Development, December 1976
7. 2008 Ocean Engineering Division (CG-432) - Specifications http://www.uscg.mil/hq/cg4/cg432/specification.asp
8. 2009 Ocean Engineering Division (CG-432) – River Buoy Prices http://www.uscg.mil/hq/cg4/cg432/2b_buoysriver.asp
9. 2009 Ocean Engineering Division (CG-432) – Foam Buoy Price List http://www.uscg.mil/hq/cg4/cg432/2b_buoysfoam.asp
10. 2009 USCG Drawing 121032 – Buoy Chain, 1983 http://www.uscg.mil/hq/cg4/cg432/docs/drawings/432B/121032h.pdf
11. OTC-2470, Colburn Jr. WE, et al, *A Lightweight Buoy for Fast Current*, Offshore Technology Conference, 1976
12. Telephone Conversation 27 July 2009 between Robert Trainor (CG-54131) and Richard Rodi (AMSEC).
13. American Institute of Steel Construction, Inc., *Manual of Steel Construction*, Edition, 1976
14. DDS-581-1 *Design Data Sheet – Calculations for Anchoring Systems*, Department of Navy, 30 September 1980
15. Baumeister T, et al, *Standard Handbook for Mechanical Engineers*, McGraw-Hill, 1967
16. Myers JJ, et al, *Handbook of Ocean and Underwater Engineering*, McGraw-Hill, 1969
17. COMDTINST M16500.3A CH-6 To Aids to Navigation Manual – Technical Manual (02/11/2005)
18. Telephone Conversations between Elizabeth Gilman (Gilman Corp.) and Richard Rodi (AMSEC)
19. Telephone Conversations between Jody Sturtze (Tideland Signal Corp.) and Richard Rodi (AMSEC)
20. *ABS Guidance Notes on the Application of Synthetic Ropes for Offshore Mooring*, American Bureau of Shipping, March 1999

APPENDIX A. FIGURES SHOWING SELECTED RIVER AND SPAR BUOYS

A.1 USCG 4th and 6th Class Buoys

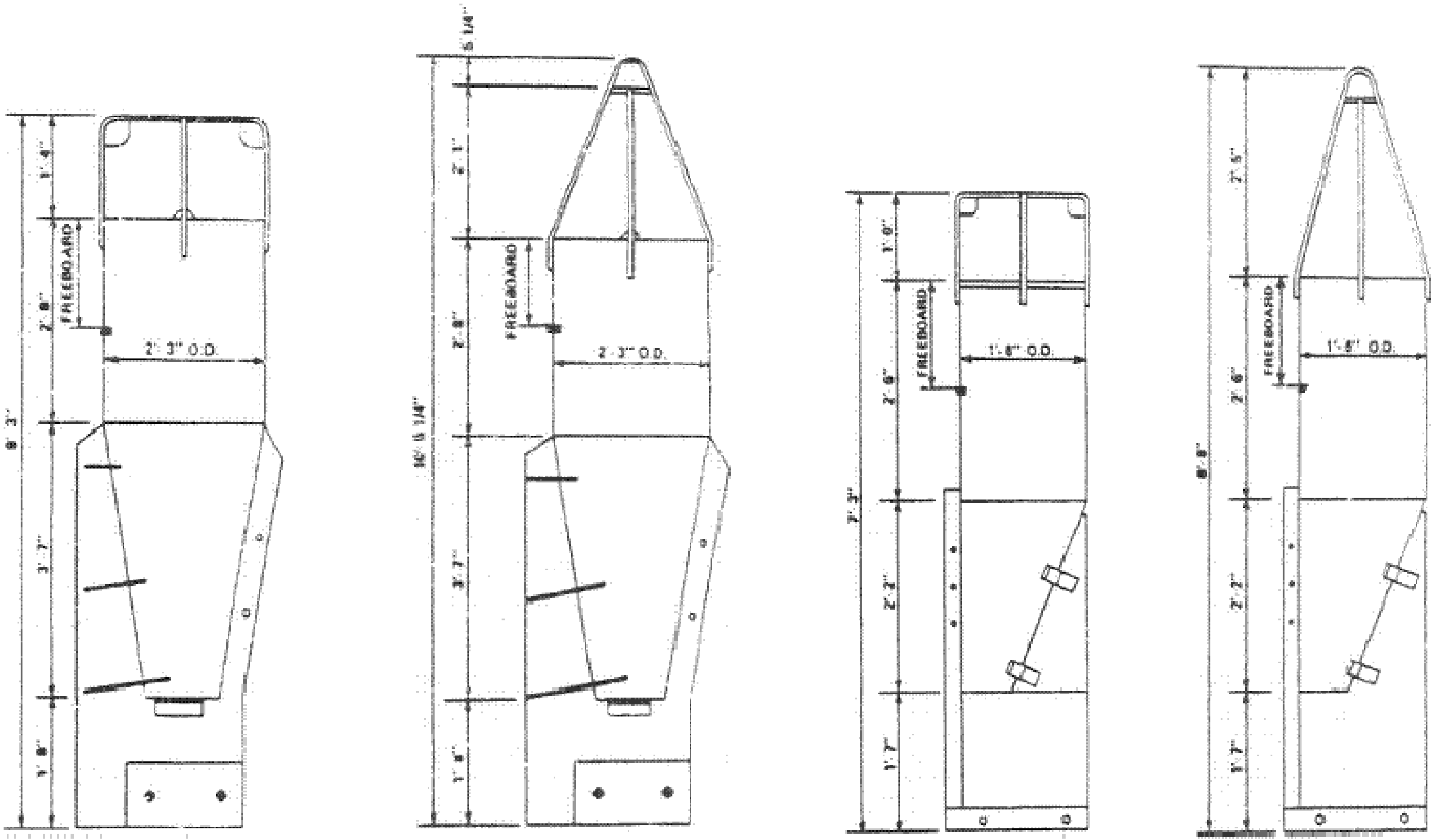


Figure A-1. 4CR, 4NR, 6CR, and 6 NR.

A.2 Canadian River Buoys

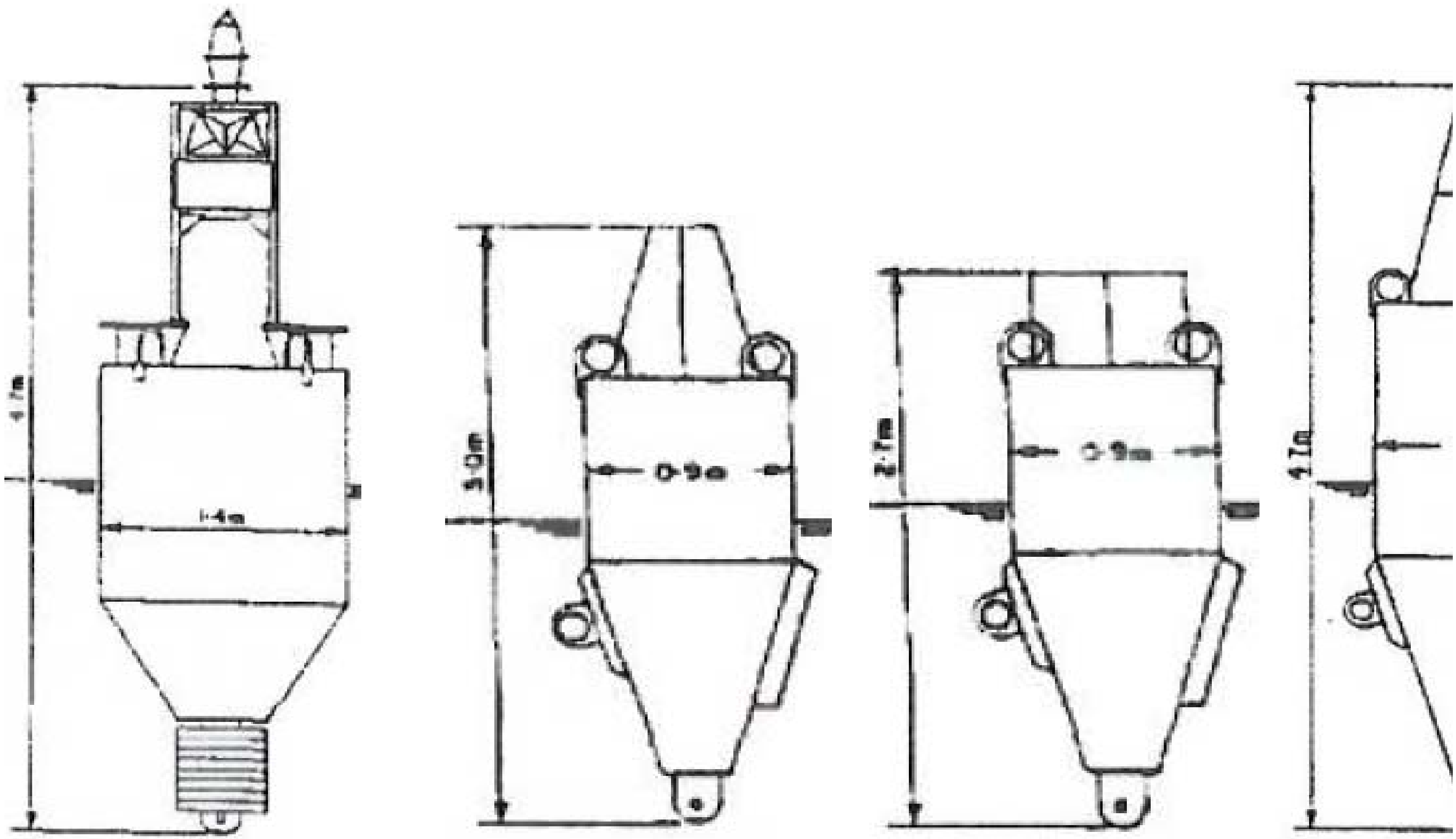


Figure A-2. FA-1001, FA-2008, FA-2009, and FA-2010.

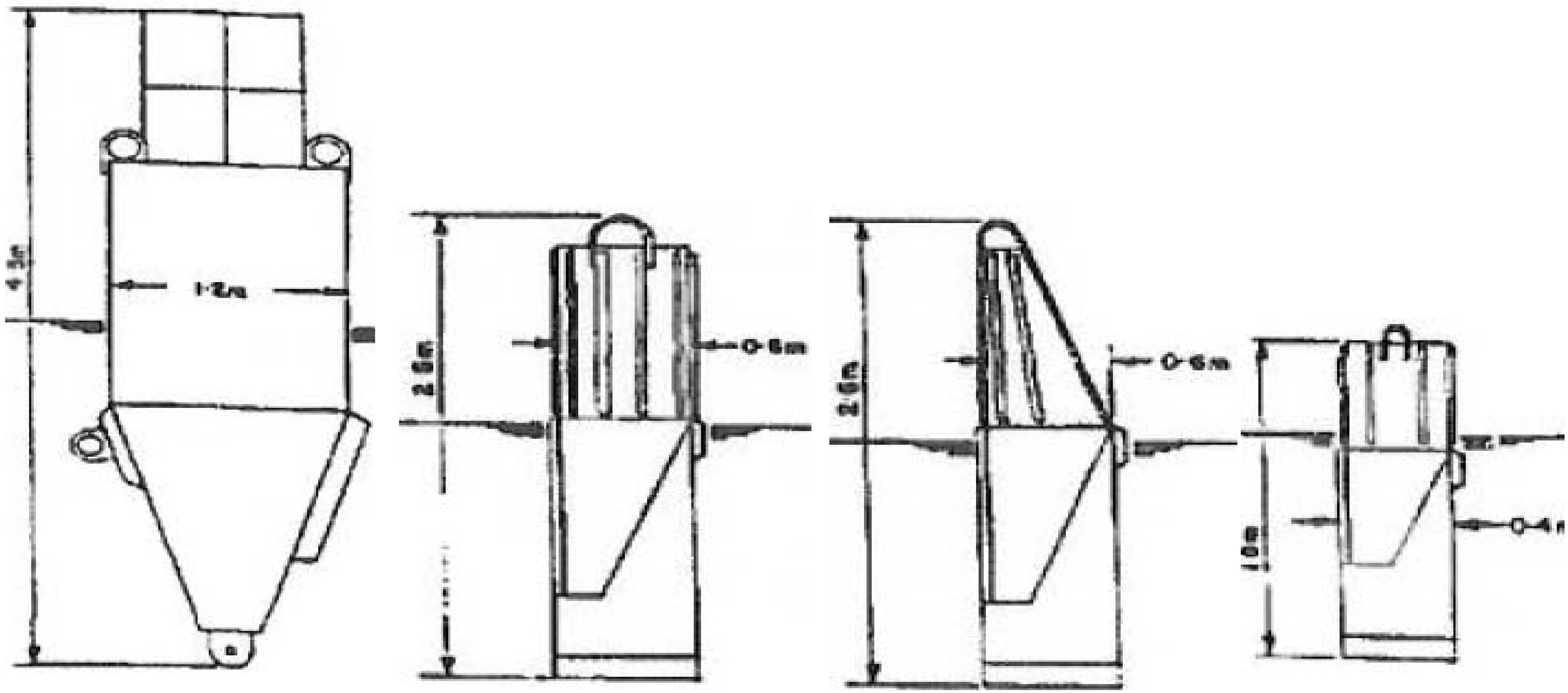


Figure A-3. FA-2011, FA-2012, FA-2013, FA-2015, and FA-2016.

A.3 Tideland, Japanese and German River Buoys

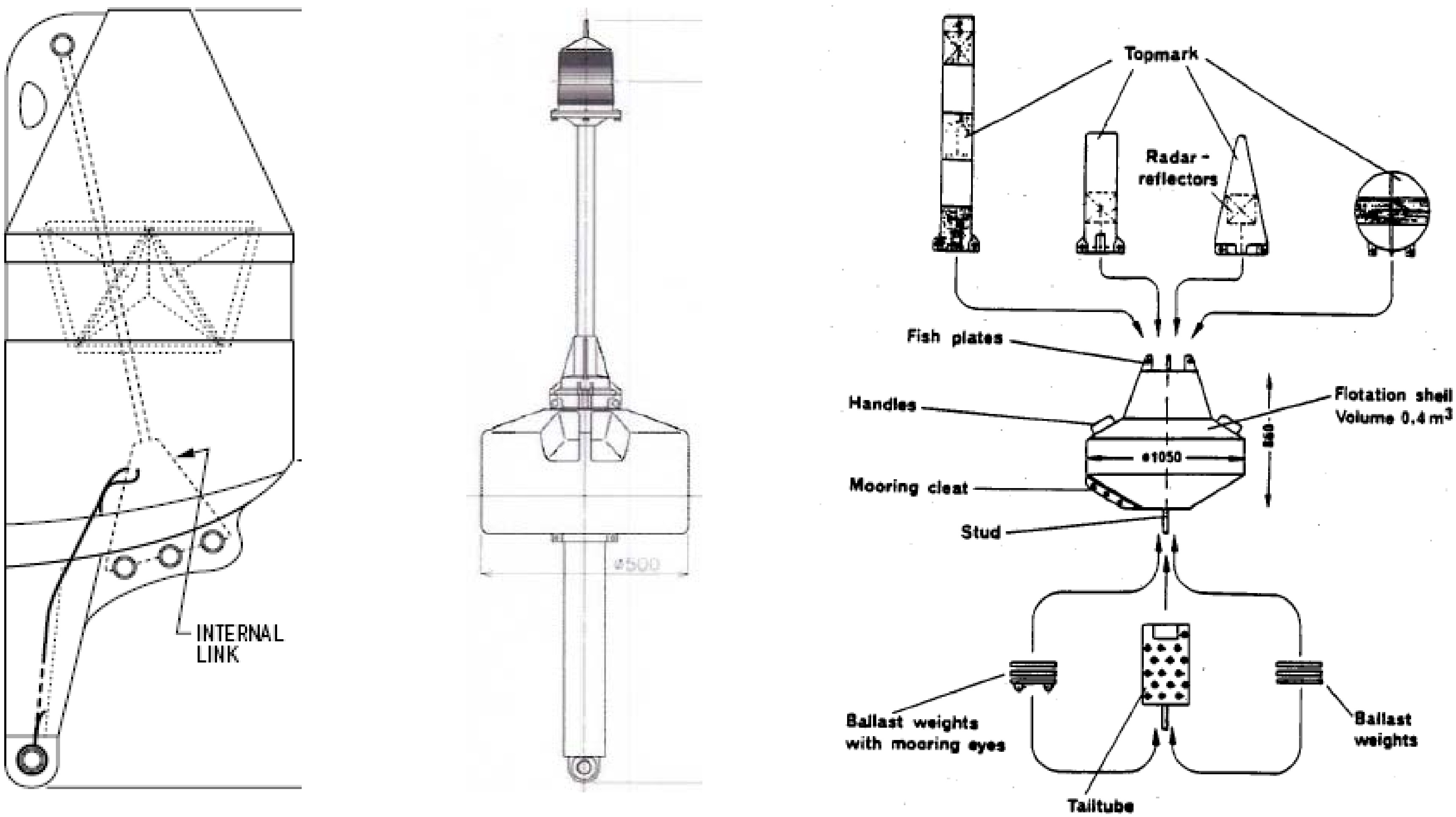


Figure A-4. Tideland SB-104, Japan CB-100, and Germany Inland Unlighted STD Steel.

A.4 Gilman Foam River Buoys

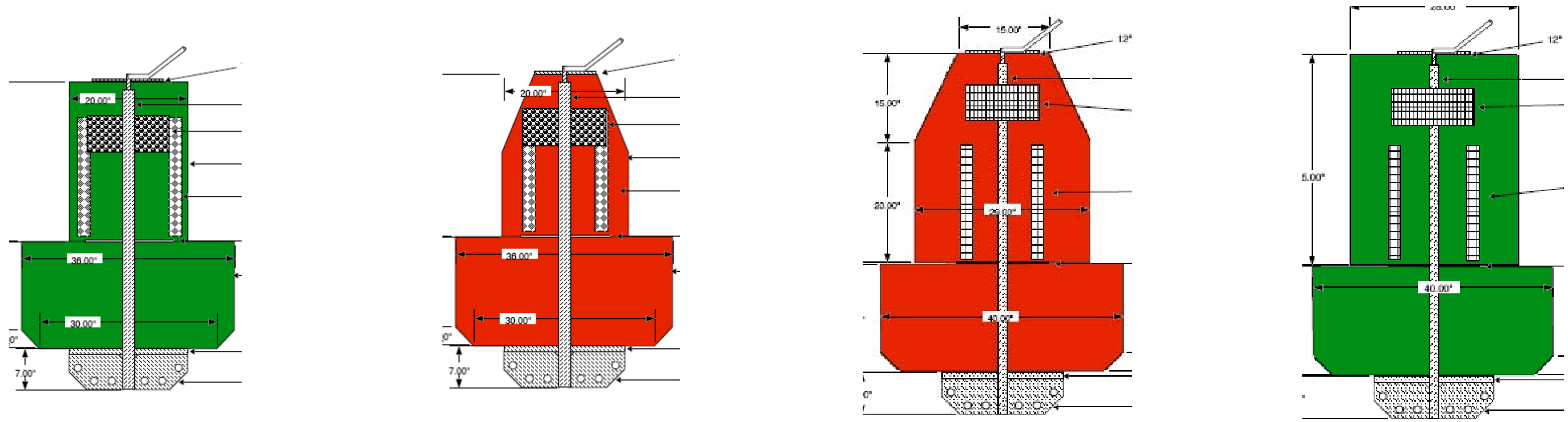


Figure A-5. FWCFR, FWNFR, 4CFR-modified, and 4NFR-modified.

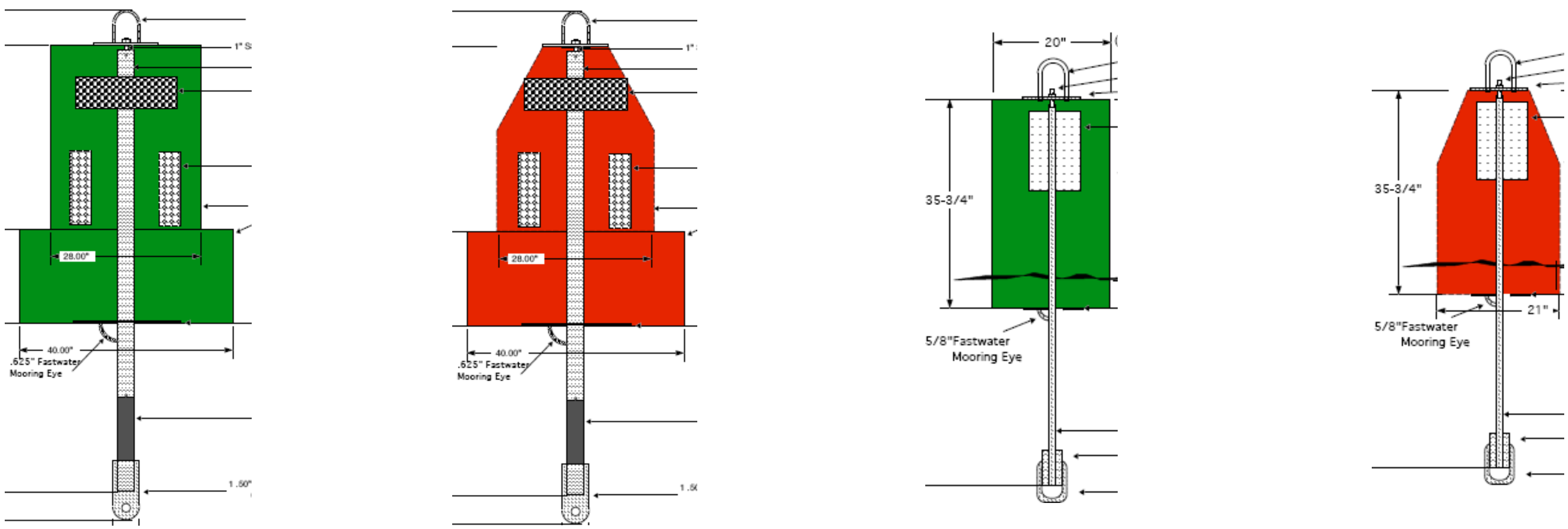


Figure A-6. 4CFR, 4NFR, 6CFR, and 6NFR.

A.5 Spar Buoys

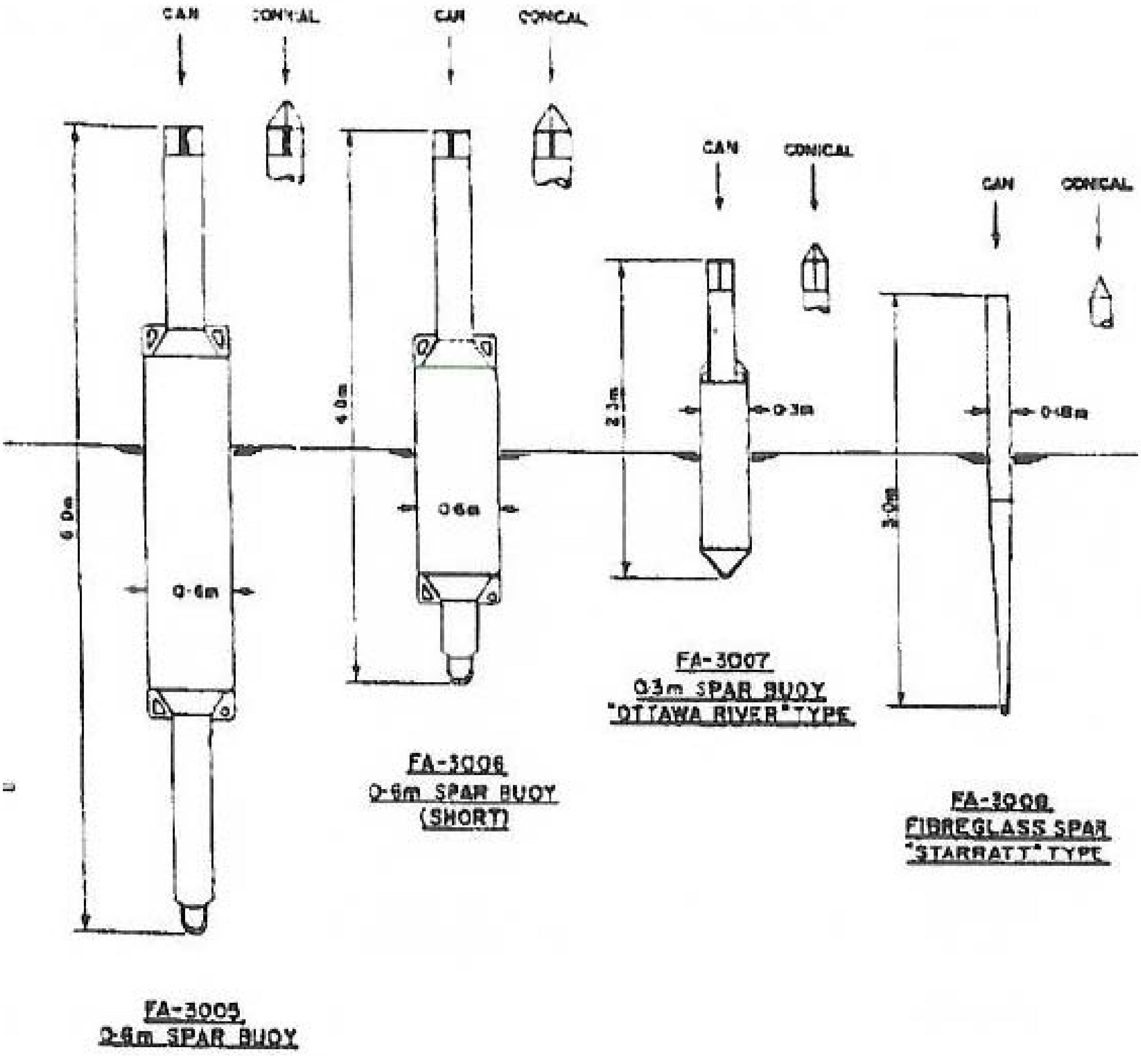


Figure A-7. Canadian FA-3005, FA-3006, FA-3007, and FA-3008.

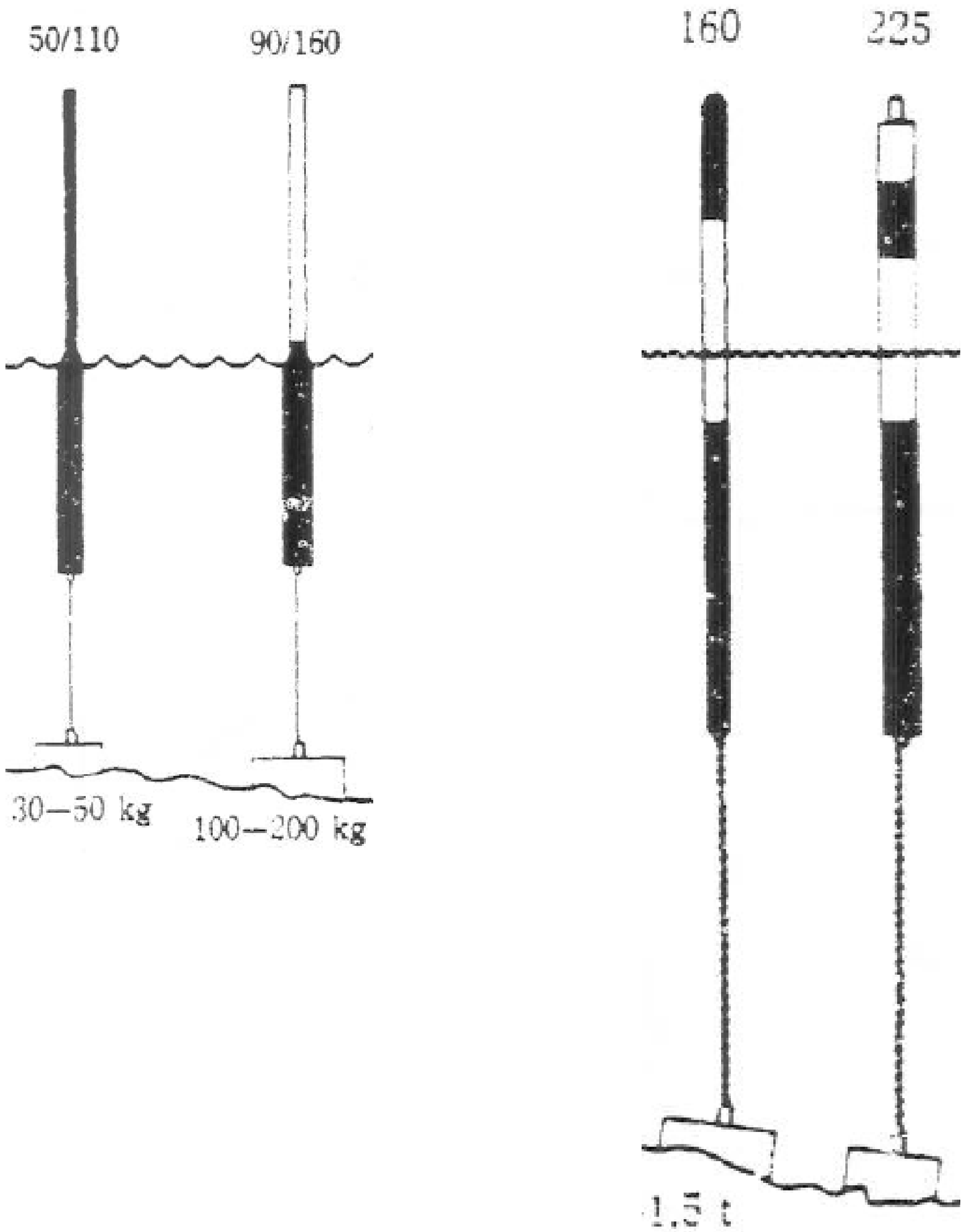


Figure A-8. Norwegian 50/110-120, 90/160, 160 x 6, and 225 x 7.

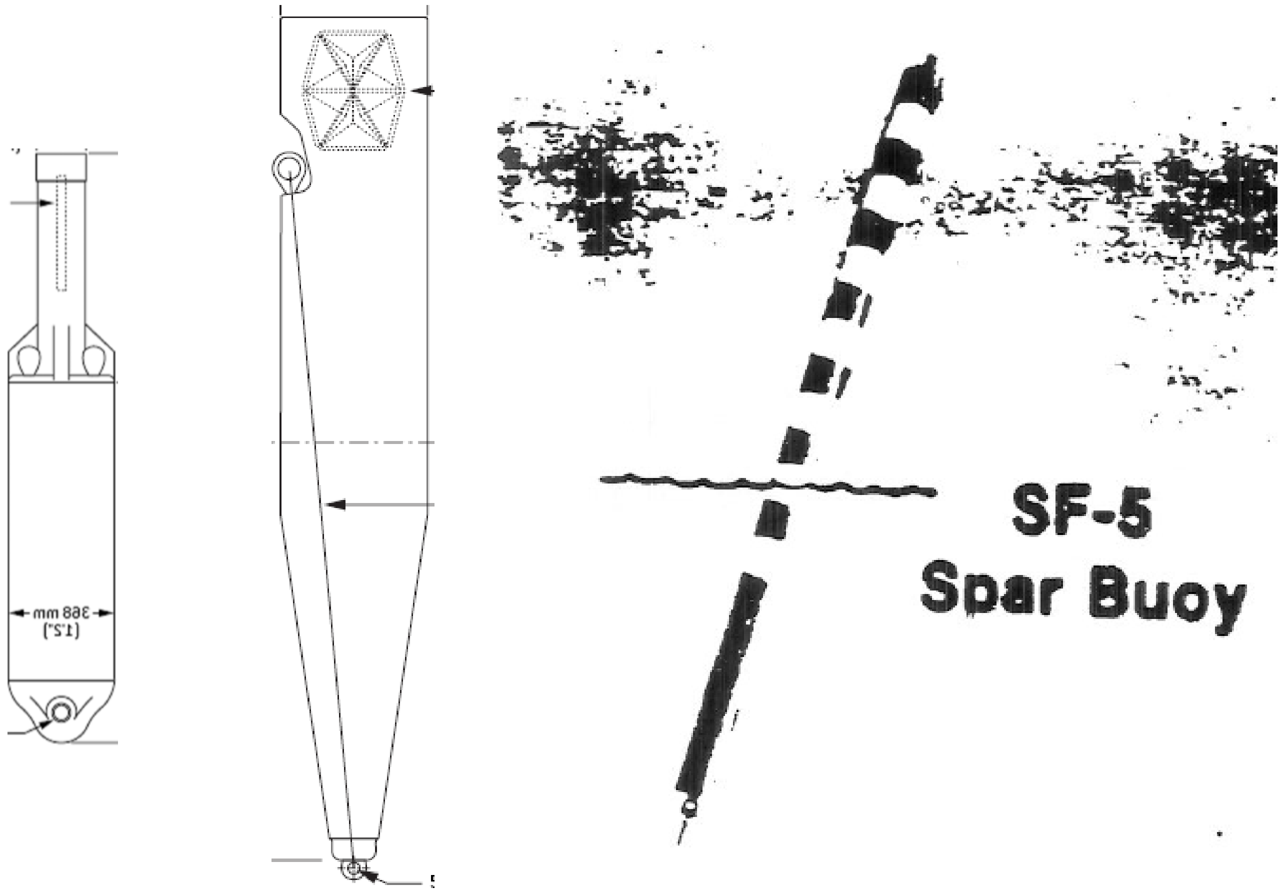


Figure A-9. Tideland SB-30 and SB-60 and USA MFG-1 SF-5.

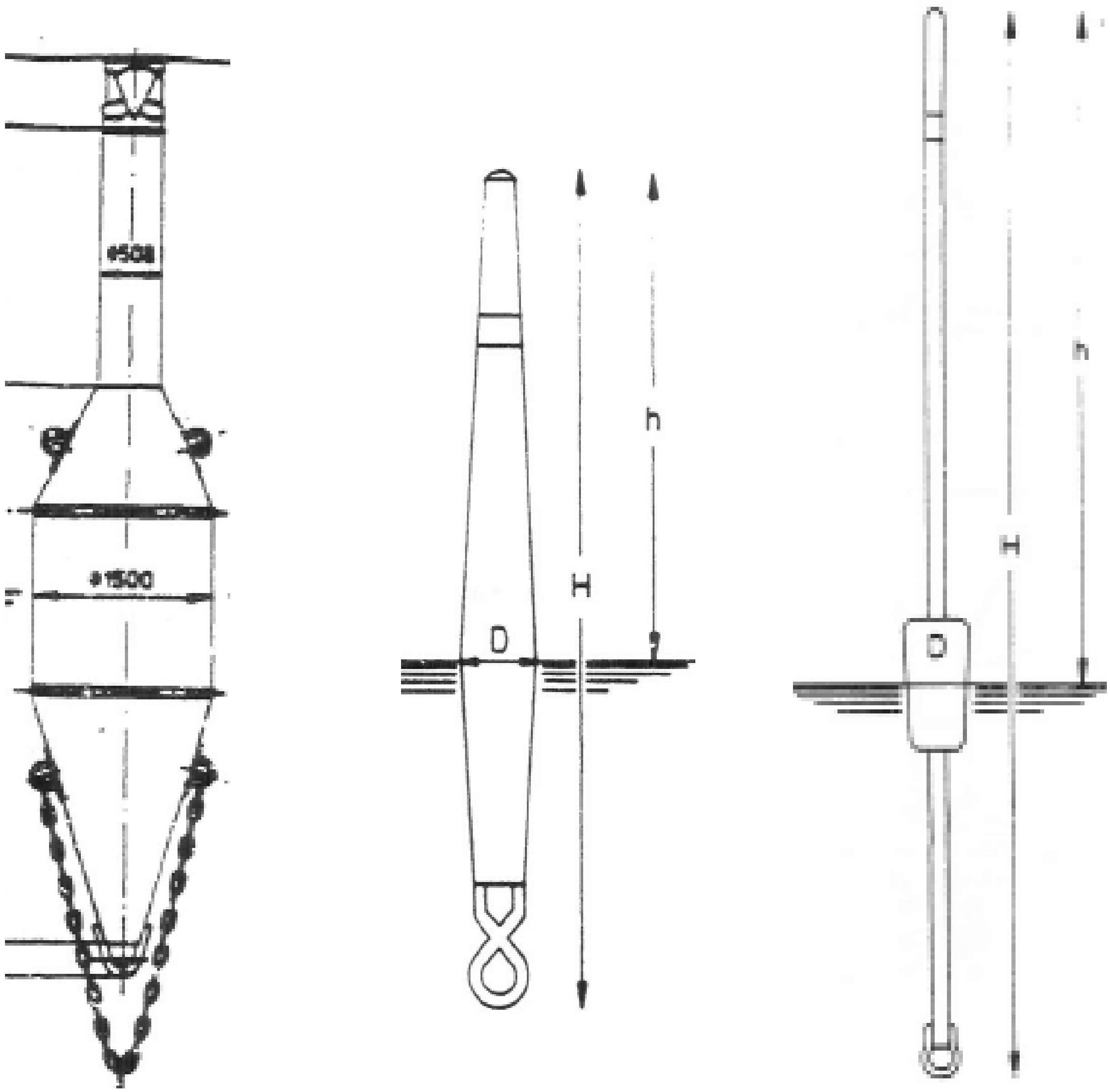


Figure A-10. T-86, Selco Type 5, and Selco Type 4.

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APPENDIX B. TRIP REPORTS TO THREE INLAND RIVER TENDERS (WLR)

B.1 B.1 USCGC KANKAKEE

The United States Coast Guard Cutter (USCGC) KANKAKEE was visited on 21 October 2008 by the following persons:

- Kurt Hansen USCG R&DC Program Manager
- Richard Rodi AMSEC LLC, R&DC Contractor
- Stan Walker CG-432
- Keith Davis CG-432
- Robert Trainor CG-54131
- Steve Hadley CG D8 DPW

The KANKAKEE is based near downtown Memphis, Tennessee, and has the lower Mississippi River as its area of responsibility (AOR). These are fast-flowing waters. The cutter operates from the Wolf River Lagoon which connects to the Mississippi River. The cutter docks at the foot of a long embankment (levee) which is typical of ports on the Mississippi. The vessel is reached by descending a long stair or parallel inclined plane. There is also an inclined railway lift for bringing buoys, sinkers, and supplies to the cutter. In spring time and wet seasons when the river rises as much as 40 ft, part of the stairs and incline are immersed and the cutter docks higher on the embankment.

The KANKAKEE is a 75-ft “pusher” tug (or towboat) which works in tandem with a 130-ft work barge. The arrangement of the combined unit can be seen in Figure B-1. The KANKAKEE faces up to the barge with a system of wire rope slings and winches that provide the connection between the vessels. The KANKAKEE provides accommodations for the USCG crew and power for pushing the unit. The work barge provides a platform for deploying and retrieving buoys and, going from forward to aft, consists of:

- Open “buoy deck” with rounded gunwales for deploying and retrieving buoys over the side. There is a spud at the forward end of the deck which is dropped down into the riverbed to hold the unit in position when working a buoy.
- A capstan on centerline of the buoy deck for retrieving buoys and “kickboards” port and starboard for launching the buoy anchor or sinker. A kickboard is shown in Figure B-2.
- A pedestal-mounted telescoping boom crane which is used for moving buoys and sinkers between the storage area and the buoy deck.
- A storage rack or “corral” for the storage of the concrete sinkers. The sinkers are stacked for storage.
- Stacks of wire rope mooring lines.
- The buoy corral for upright storage of the buoys. The green can buoys are stored on the port side and the red nun buoys are stored on the starboard side, which allows for efficient deployment and retrieval of the boys as the KANKAKEE moves up-river.
- A small deckhouse behind the buoy corral which provides a workshop and storage. Two aluminum work/rescue boats are stowed atop the deckhouse.

Figure B-1. USCGC KANKAKEE at Memphis.

For the stretch of the Mississippi River that is the KANKAKEE's AOR, it deploys and retrieves 4th Class buoys exclusively, using 90 ft of ½-in. wire rope attached to a 1,500 lb concrete sinker. At the start of the visit, the crew demonstrated the setting and recovery of a buoy while the cutter was still at the dock. To deploy a buoy, the sinker is set on a kickboard launching mechanism at the barge side by the barge crane; see Figure B-2. The buoy is placed at the barge side, with the coiled wire rope connecting the buoy and the sinker. When the kickboard is released, the sinker tips into the river and the wire pays out. The buoy is then pushed over the side by two crew members.

Figure B-2. Sinker and mooring on kickboard.

To recover a buoy, the crew lassoes the buoy using a wire rope lariat with a running noose. The buoy is held against the barge by the lasso and a hook at the end of a wire rope is attached to a lifting eye at the top of the buoy. The buoy is then pulled aboard using the barge's centerline capstan. When the buoy is pulled up on the deck, the mooring line is detached from the buoy and pulled up using the capstan until the sinker is brought up on deck. The buoy is then removed to the storage pen (corral) and a new buoy is placed ready for launching. The wire rope and sinker may be reused, depending on condition. If the sinker is to be reused, it will be launched directly from the deck by a crew member using two pinch bars rather than lifting it onto the kickboard. See Figure B-3.

Figure B-3. Crew ready to set buoy using pinch bars to launch sinker.

After demonstrating buoy handling techniques in the lagoon, the KANKAKEE got underway and onto the Mississippi River to demonstrate actual buoy retrieval and deployment operations. The work of the fast-water tenders consists primarily of resetting buoys to mark the boundaries of the 12-ft channel as the river rises and falls seasonally. In this operation, the buoy, mooring, and sinker are retrieved and reset. Thus the entire buoy system is inspected regularly and damaged or worn components are replaced as required. Additionally, the cutters replace damaged, worn, and diving buoys. Because of the winding nature of the river and the fact that the tow pilots have depth sounders and know the river, buoys on turns are frequently run over by the tows, with consequent contact damages and/or complete loss of the buoys.

The fast waters tend to cause the buoys to become inclined, which reduces visibility and radar reflectivity. The inclination can be controlled by the location of the mooring connection on the buoy, as multiple holes are available. Attachment above the center of resistance will cause the buoy to lean into the current, while attachment at a lower point will cause the buoy to lean away from the current. The attachment point can be varied seasonally by the WLR crew as the buoys are reset, allowing the buoy to remain upright, despite the current. See Figure B-4. (Note: The series of attachment points is visible in Figure 7 and Figure 14.)

Figure B-4. Buoy leaning into current.

Also, debris floating in the river during the spring floods can become caught on the buoy and/or mooring causing the buoy to incline further and dive; i.e., become totally immersed. While the resetting of buoys is an extremely efficient process, with only a few minutes spent on station, the location and recovery of diving buoys can sometimes take 1 to 2 hours.

B.2 USCGC OUACHITA

The USCGC OUACHITA was visited on 23 October 2008 by the following persons:

- Kurt Hansen USCG R&DC Program Manager
- Richard Rodi AMSEC LLC, R&DC Contractor
- Stan Walker CG-432
- Keith Davis CG-432
- Robert Trainor CG-54131

The OUACHITA is based on Chickamauga Lake above the Chickamauga Dam on the Tennessee River in eastern Chattanooga, Tennessee, and has the Tennessee River as its AOR. These are pooled waters upriver and downriver of the dam. The OUACHITA is a 65-ft pusher tug which works in tandem with a 99-ft work barge. The arrangement is similar to that of the KANKAKEE, except that barrels of chain are stored forward of the concrete sinkers. See Figure B-5.

Figure B-5. USCGC OUACHITA at Chattanooga.

The OUACHITA sets and retrieves 4th Class buoys, using 45 ft (half shot) of ½-in. chain attached to a 1,500 lb concrete sinker. At the start of the visit, the crew demonstrated the deployment and recovery of a buoy while the cutter was at the dock, which was similar to the procedure on the KANKAKEE except that chain is used for the mooring instead of wire. See Figure B-6.

Figure B-6. 4th Class buoy, chain, and sinker ready to be set.

To recover a buoy, the crew uses a boat hook to grab the buoy from one of the lifting eyes at the top of the buoy. A second pole with a snap hook attached is used to secure a wire rope to a lifting eye. The wire rope is used to pull the buoy aboard using the barge's centerline capstan. When the buoy is pulled up on the deck, the mooring chain is detached from the buoy and may be pulled up using the capstan if the buoy is to be reset. The buoy is then removed to the storage corral and a new buoy is placed ready for launching. The chain and sinker will typically be reused if the buoy is not reset. See Figure B-7.

Figure B-7. Buoy recovery using boat hook and wire rope on pole.

After demonstrating buoy handling techniques at the dock, the OUACHITA deployed downriver through the Chickamauga Lock and onto the Tennessee River to perform actual buoy recovery and setting operations. The work of the pooled water tenders consists primarily of replacing faded or damaged buoys, as the river level is controlled by the dams and no seasonal resetting of the buoys is required to accommodate the rise and fall, which is only a few feet. Because the buoys are not reset on frequent schedule, the chain and sinker are not inspected regularly. However, the buoys are replaced every 3 years because of the need to replace the chain. The buoy's life expectancy may exceed that of the chain; however, when a chain is replaced, a new buoy is used instead of the existing. This is done to match a new buoy to a new mooring and ensure a 3-year life if the buoy is not damaged. The maintenance operation for buoys is performed at the base station. Buoys pulled because of chain replacement are evaluated, repaired, and repainted, as necessary, and replaced in the buoy inventory.

The OUACHITA has 1,300 buoys in its AOR. As there are only two regularly scheduled tows in the AOR, most of the traffic is recreational, and few buoys are damaged by the tows. During our visit, most buoys were replaced because of reduced visibility caused by color fading or excess amounts of bird droppings. One buoy was sitting low in the water and was retrieved. When punctured on deck with a fire axe, water flowed out, indicating a leaking condition probably caused by corrosion.

B.3 USCGC OSAGE

The USCGC OSAGE was visited on 9 December 2008 by the following persons:

- Kurt Hansen — USCG R&DC Program Manager
- Richard Rodi — AMSEC LLC, R&DC Contractor
- Wayne Danzik — CG-432
- Robert Trainor — CG-54131

The OSAGE is based on Sewickley, Pennsylvania, below the Emsworth Dam on the Ohio River, downriver of Pittsburgh. The OSAGE has the Ohio, Monongahela, and Allegheny Rivers as its AOR. These are pooled waters upriver and downriver of the dam. The OSAGE is a 65-ft pusher tug, a sister ship to the OUACHITA and works with a similar 99-ft barge which provides the storage, platform, and equipment for working the buoys. There are two 12-ft by 9-ft buoy storage pens (corrals) on the barge. On the day of our visit, the barge had 64 6^{th} Class buoys and 16 4^{th} Class buoys stowed. See Figure B-8.

Figure B-8. USCGC OSAGE on the Monongahela River.

The OSAGE sets and retrieves 4th Class and 6th Class buoys, using 90 ft (one shot) of ½-in. chain attached to a 1,500 lb concrete sinker. To recover a buoy, the crew lassoes the buoy using procedure similar to that used on the KANKAKEE. Once the buoy is brought alongside, a wire rope is attached to a lifting eye which is used to pull the buoy aboard using the barge's centerline capstan. When the buoy is pulled up on the deck, the mooring chain is detached from the buoy and may be pulled up using the capstan if the buoy is to be reset. The buoy is then removed to the storage pen (corral) and a new buoy is placed ready for launching. The chain and sinker will typically be reused and not inspected if the buoy is not moved. See Figure B-9.

Figure B-9. Buoy recovery using lasso.

During the visit, the OSAGE deployed upriver through the Emsworth Lock and onto the Monongahela River to perform actual buoy recovery and setting operations. The work of the OSAGE consists primarily of replacing damaged buoys, as the river level is controlled by the dams and no seasonal resetting of the buoys is required to accommodate the rise and fall, which is 5 ft on the Monongahela and 10 ft on the Ohio River. Because the buoys are not reset, the chain and sinker are not inspected regularly. During the visit, six buoys were replaced: three had been run over by tows and three had chain/shackle problems.

There are more than 500 buoys in the OSAGE AOR, with 95 4th Class buoys and 426 6th Class buoys deployed. There is significant traffic on the Monongahela River, with most of the tows moving coal to coking plants. The average buoy life is 2 years, with most of the buoys damaged by the tows.

APPENDIX C. BUOY DATA FOR CURRENT VELOCITY VERSUS FREEBOARD

Table C-1. 4th Class buoy: current velocity versus freeboard.

	USCG 4CR		Gilman FWCFR		Gilman 4CFR	
	Weight = 465.0 lbs		Weight = 200.0 lbs		Weight = 195.0 lbs	
	Height = 9.3 ft		Height = 4.7 ft		Height = 7.0 ft	
v (knots)	F_D (lbs)	Freeboard (ft)	F_D (lbs)	Freeboard (ft)	F_D (lbs)	Freeboard (ft)
0.1	0.11	3.74	0.02	3.67	0.04	3.90
0.5	2.76	3.71	0.50	3.67	0.90	3.90
1.0	11.37	3.62	2.03	3.67	3.63	3.89
1.5	26.90	3.47	4.65	3.66	8.33	3.88
2.0	51.21	3.25	8.48	3.65	15.21	3.86
2.5	87.17	2.95	13.67	3.64	24.58	3.84
3.0	139.19	2.56	20.46	3.62	36.86	3.81
3.5	209.17	2.14	29.16	3.60	52.60	3.78
4.0	291.65	1.84	40.15	3.57	72.52	3.74
4.5	406.78	1.35	53.97	3.54	97.54	3.69
5.0	Sub	Sub	71.30	3.51	128.88	3.63
5.5	Sub	Sub	93.04	3.46	168.12	3.56
6.0	Sub	Sub	120.40	3.41	211.33	3.50
6.5	Sub	Sub	154.99	3.35	258.29	3.46
7.0	Sub	Sub	195.84	3.28	313.59	3.41
7.5	Sub	Sub	235.11	3.25	379.05	3.35
8.0	Sub	Sub	281.27	3.20	457.16	3.28

	Canada FA-2012		Tideland SB-104		4th Class Can Hybrid	
	Weight = 350.0 lbs		Weight = 160.0 lbs		Weight = 230.0 lbs	
	Height = 8.8 ft		Weight = 6.0 lbs		Height = 7.3 ft	
v (knots)	F_D (lbs)	Freeboard (ft)	F_D (lbs)	Freeboard (ft)	F_D (lbs)	Freeboard (ft)
0.1	0.10	3.22	0.04	2.95	0.06	3.93
0.5	2.40	3.20	1.09	2.94	1.46	3.92
1.0	9.77	3.15	4.39	2.93	5.96	3.89
1.5	22.67	3.06	9.92	2.90	13.79	3.85
2.0	42.00	2.94	17.75	2.87	25.50	3.78
2.5	69.07	2.77	27.97	2.82	41.85	3.70
3.0	105.68	2.57	40.67	2.77	63.88	3.59
3.5	154.29	2.32	55.99	2.71	93.06	3.46
4.0	213.94	2.09	74.04	2.64	131.36	3.30
4.5	282.80	1.92	95.00	2.57	181.56	3.11
5.0	367.39	1.71	119.03	2.49	235.39	2.99
5.5	471.80	1.44	146.33	2.40	299.76	2.86
6.0	601.90	1.11	177.13	2.30	378.48	2.70
6.5	Sub	Sub	210.33	2.23	475.69	2.51
7.0	Sub	Sub	246.37	2.17	597.46	2.27
7.5	Sub	Sub	285.88	2.11	752.96	1.96
8.0	Sub	Sub	329.08	2.04	956.75	1.55

Table C-2. 6th Class buoy: current velocity versus freeboard.

	USCG 6th Class 6CR		Gilman 6CFR Buoy		Tideland SB-30		6th Class Hybrid	
	Weight = 160.0 lbs		Weight = 63.0 lbs		Weight = 136.0 lbs		Weight = 77.0 lbs	
	Height = 7.3 ft		Height = 5.5 ft		Height = 7.1 ft		Weight = 5.3 lbs	
v (knots)	F_D (lbs)	Freeboard (ft)	F_D (lbs)	Freeboard (ft)	F_D (lbs)	Freeboard (ft)	F_D (lbs)	Freeboard (ft)
0.1	0.07	2.39	0.03	1.99	0.07	3.13	0.04	2.36
0.5	1.68	2.37	0.84	1.98	1.64	3.09	1.11	2.35
1.0	6.92	2.30	3.46	1.95	6.95	2.81	4.56	2.30
1.5	16.24	2.18	8.09	1.90	17.28	2.10	10.72	2.22
2.0	30.61	2.01	15.22	1.83	36.47	0.69	20.27	2.10
2.5	51.55	1.78	25.57	1.73	Sub	Sub	34.29	1.94
3.0	81.29	1.47	40.31	1.59	Sub	Sub	54.48	1.72
3.5	Sub	Sub	61.21	1.41	Sub	Sub	83.46	1.42
4.0	Sub	Sub	91.00	1.17	Sub	Sub	125.33	1.02
4.5	Sub	Sub	134.00	0.84	Sub	Sub	186.72	0.48
5.0	Sub	Sub	194.03	0.44	Sub	Sub	Sub	Sub
5.5	Sub	Sub	253.36	0.22	Sub	Sub	Sub	Sub
6.0	Sub	Sub	Sub	Sub	Sub	Sub	Sub	Sub
6.5	Sub	Sub	Sub	Sub	Sub	Sub	Sub	Sub
7.0	Sub	Sub	Sub	Sub	Sub	Sub	Sub	Sub